Cycles of Critical Metals

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Dissipative Losses and Potential Optimizations

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ABSTRACT

Many materials have a growing importance for our society as well as a growing supply risk, which together is referred to as the criticality of materials. Many metals, particularly those that are frequently considered to be critical, are used in dissipative ways along the product life cycle. Concurrently, there is a lack of consensus in nomenclature on dissipation as well as of methodological approaches to assess dissipation. This has been addressed in this thesis by providing a concise definition and classification of dissipative losses, by implementing this definition into the material flow analysis methodology, and by exemplarily applying the methodology to selected metals, which are most frequently considered to be critical. The analysis focuses on selected applications: indium and gallium in CIGS photovoltaic cells, germanium in polymerization catalysts, and yttrium in thermal barrier coatings in aircraft engines. The outcomes of the prospective case studies, which focus on products used in Germany, include information on the hot spots regarding the occurrence of different types of dissipative losses and potential optimizations. Such knowledge is of value for achieving a more sustainable materials management which reduces environmental impacts of material use. Based on the methodological description and case study outcomes provided in this thesis, future studies with similar scope may be facilitated significantly.

ZUSAMMENFASSUNG

Eine Vielzahl von Materialien weist eine stetig steigende Bedeutung für unsere Gesellschaft sowie ein wachsendes Versorgungsrisiko auf. Die Kombination beider Faktoren wird als Kritikalität von Materialien bezeichnet. Viele Metalle – insbesondere solche, die besonders häufig als kritisch angesehen werden – werden auf Weisen genutzt, die zum dissipativen Verlust entlang des Produktlebenszyklus führen. Bezüglich der Dissipation von Materialien lässt sich jedoch ein fehlendes einheitliches Verständnis bezüglich der Nomenklatur sowie methodischer Ansätze zur Quantifizierung und Erfassung von Dissipation feststellen. Dies wird in dieser Dissertation aufgegriffen, indem eine prägnante Definition dissipativer Verluste und ein Schema zu deren Klassifizierung präsentiert und deren Implementierung in die Methodik der Materialflussanalyse beschrieben werden. Die Methodik wird in einer prospektiven Untersuchung exemplarisch auf verschiedene Metalle, die besonders häufig als kritisch angesehen werden, entlang des Lebenszyklus ausgewählter Produkte angewendet: Indium und Gallium in CIGS Photovoltaikzellen, Germanium in Polymerisationskatalysatoren und Yttrium in keramischen Hitzeschutzbeschichtungen. Der Fokus der Untersuchung liegt dabei auf Produkten, die in Deutschland eingesetzt werden. Die Ergebnisse der Fallstudien beinhalten Erkenntnisse über den Ort und den Umfang auftretender dissipativer Verluste, deren Typ entsprechend des Klassifizierungsschemas sowie potentieller Optimierungsmaßnahmen. Die Erkenntnisse sind eine wertvolle Grundlage für eine Entwicklung hin zu einem nachhaltigeren Materialmanagement mit deutlich reduzierten Umweltwirkungen. Auf Basis der in dieser Dissertation beschriebenen Methodik sowie den Ergebnissen der Fallstudien, kann der Aufwand für zukünftige Studien mit ähnlichen Untersuchungsrahmen deutlich reduziert werden.

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LIST OF ABBREVIATIONS

B2B	Bottle-to-Bottle
B2C	Business-to-Consumer
CDL	Cumulative Dissipative Losses
CdTe	Cadmium-Telluride
CIGS	Copper-indium-gallium-diselenide
CIS	Copper-indium-di-selenide
CGS	Copper-gallium-di-selenide
cf.	confer (compare)
CPME	Committee of PET Manufacturers in Europe
e.g.	example given
EEE	Electrical and electronic equipment
ElektroG	Elektro- und Elektronikgerätegesetz
Env	Environment
EOL	End-of-life
EU	European Union
F&M	Fabrication and manufacturing
FM	Fabrication and manufacturing
Gg	Gigagram
ICT	Information and communications technology
IDA	Institute for Defense Analyses
i.e.	*id est* (latin: that is; that means)
ITO	Indium tin oxide
JRC	Joint Research Center
kg	Kilogram
kt	Kilotons
LaNiH	Lanthanum-nickel-hydrogen
LCD	Liquid crystal display
LED	Light emitting diode
LF	Landfill
MFA	Material flow analysis
Mg	Megagram
MP	Material production
MRI	Magnetic resonance imaging
OECD	Organization for Economic Co-operation and Development
OMF	Other material flows
PET	Polyethylene terephthalate
PGM	Platinum group metals
pom	Placed on the market
ppm	Parts per million

PV	Photovoltaic
RC	Recycled content
RE	Rare earth
REE	Rare earth elements
REO	Rare earth oxides
SFA	Substance flow analysis
SMM	Sustainable Materials Management
t	Tons
TBC	Thermal barrier coating
TCO	Transparent conducting oxide
U.S.	United States (of America)
USGS	United States Geological Survey
WEEE	Waste Electrical and Electronic Equipment
wt.-%	Weight percentage
YSZ	Yttrium stabilized zirconia

List of Chemical Elements and Compounds

Ag	Silver
Al:ZnO	Aluminum doped zinc oxide
As	Arsenic
Au	Gold
Be	Beryllium
Bi	Bismuth
Cd	Cadmium
Ce	Cerium
CeO_2	Cerium oxide
Co	Cobalt
Cr	Chromium
Cu	Copper
Dy	Dysprosium
Dy_2O_3	Dysprosium oxide
Er	Erbium
Er_2O_3	Erbium oxide
Eu	Europium
Eu_2O_3	Europium oxide
F:SnO	Fluor doped tin oxide
Fe	Iron
Ga	Gallium
Gd	Gadolinium
Gd_2O_3	Gadolinium oxide
Ge	Germanium
GeO_2	Germanium dioxide
H	Hydrogen
Ho	Holmium
Ho_2O_3	Holmium oxide
In	Indium
Ir	Iridium
La	Lanthanum
La_2O_3	Lanthanum oxide
Li	Lithium
Lu	Lutetium
Lu_2O_3	Lutetium oxide
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
Nb	Niobium
Nd	Neodymium
Nd_2O_3	Neodymium oxide
Ni	Nickel
NO_x	Nitrogen oxides
O	Oxygen
Os	Osmium
Pb	Lead
Pd	Palladium
Pr	Praseodymium
Pr_6O_{11}	Praseodymium oxide
Pt	Platinum
Re	Rhenium
Rh	Rhodium
Ru	Ruthenium
S	Sulfur
Sb	Antimony
Sc	Scandium
Se	Selenium
Si	Silicon
Sm	Samarium
Sm_2O_3	Samarium oxide
Sn	Tin
SO_2	Sulfur dioxide
Sr	Strontium
Ta	Tantalum
Tb	Terbium
Tb_4O_7	Terbium oxide
Te	Tellurium
Tm	Thulium
Tm_2O_3	Thulium oxide
U	Uranium
V	Vanadium
W	Tungsten
Y	Yttrium
Y_2O_3	Yttrium oxide
Yb	Ytterbium
Yb_2O_3	Ytterbium oxide
Zn	Zinc

PREFACE AND ACKNOWLEDGMENT

This thesis is an intellectual product of the author, Till Zimmermann. Parts of this thesis have previously been published in the following publications:

- Zimmermann, Till, and Stefan Gößling-Reisemann. 2013. "Critical materials and dissipative losses: a screening study." *Science of The Total Environment* 461-462: 774–80. doi: 10.1016/j.scitotenv.2013.05.040.
- Zimmermann, Till. 2013. "Dynamic material flow analysis of critical metals embodied in thin-film photovoltaic cells." artec paper 194. artec paper 194. artec-Research Center for Sustainability Studies, artec-Research Center for Sustainability Studies, University of Bremen, Bremen, Germany.
- Zimmermann, Till, and Stefan Gößling-Reisemann. 2014. "Recycling Potentials of Critical Metals-Analyzing Secondary Flows from Selected Applications." *Resources* 3 (1): 291–318. doi: 10.3390/resources3010291.
- Zimmermann, Till, and Stefan Gößling-Reisemann. 2015. "Dynamic Product Centric-MFA." In *Handbook of Research Methods and Applications in Environmental Studies*. Edited by Matthias Ruth: Edward Elgar Pub.

Another article titled "Uncovering the fate of critical metals" is planned for publication in the Journal of Industrial Ecology, covering the results of the case study analysis.

Parts of this thesis or closely related papers were presented at the following conferences:

- World Resources Forum 2011 in Davos (title of contribut*ion: Critical metals and dissipative losses: a screening study*),
- Gordon Research Conference on Industrial Ecology 2012 in Les Diablerets (title of contribution: *Dissipation in critical metal cycles: loop holes, potential optimizations and dissipative losses*),
- ISIE MFA ConAccount Section Conference 2012 in Darmstadt (title of contribution: *Dissipative losses of critical metals: A quantification and classification approach*),
- Life Cycle Management (LCM) Conference 2013 in Gothenburg (title of contribution: *Historic and future flows of critical materials resulting from deployment of photovoltaics*),
- 11th ISIE Socio-Economic Metabolism Section Conference 2014 in Melbourne (title of contribution: *Dissipative losses of critical metals in prospective product-centric MFA*), and
- ISIE conference 2015 in Surrey (title of contribution: *Losing critical metals: tracking dissipative losses from material production to end-of-life*).

While I alone am responsible for this thesis, it is also a product of years of interaction with, and inspiration by, a large number of friends and colleagues: I would therefore like to thank my PhD advisor, Professor Stefan Gößling-Reisemann for supporting me during these past four years. Stefan has been supportive while giving me all the freedoms I needed. I also have to thank Professor Arnim von Gleich, the members of my PhD committee and in particular Ester van der Voet for agreeing to become a reviewer. I also thank my fellow PhD student, Henning Wigger, Christian Pade, Urte Brand, Sönke Stührmann, and Birgit Lutz-Kunisch, for many valuable discussions and feedback.

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1 INTRODUCTION

Metals have become ubiquitous in our society. A number of metals that has grown rapidly over the past few decades is used in many different ways and products –many of which leading to dissipative losses somewhere in their life cycle. From raw material production to product fabrication and manufacturing (F&M), use phase, and end-of-life, material losses can be observed being reflected for example in end-of-life (EOL) recycling rates[1] below one percent for more than 30 metals in the periodic table (e.g., Graedel et al. 2011a). Finite resources are taken from the environment, used in the technosphere[2], and getting lost in ways making their recovery unfeasible.

While the mining of apparently finite resources such as metals is "*unanimously considered as unsustainable*"[3] (Mudd and Ward 2008), contributing to a development towards a more sustainable metals management (SMM) can be considered as the overriding goal of this work. By the OECD (2010) SMM is defined as "*an approach to promote sustainable materials use, integrating actions targeted at reducing negative environmental impacts and preserving natural capital throughout the life cycle of materials […]*." (OECD 2010). Other authors emphasize closed loops, which ought to be free of quantity and quality losses, and avoidance of dissipative losses as integral parts of a sustainable metals industry (Gleich 2006). Given the growing importance and difficult supply situation (i.e., the criticality) of metals like the rare earth elements (REE), indium, gallium or germanium, working towards a sustainable metals industry seems naturally for these metals. By working towards a more sustainable metals management, resource dependencies can be minimized which is urgently needed especially for metals commonly considered as critical in terms of their risk of supply and (economic) importance. Furthermore, by increasing the efficiency of the way in which materials are used by closing the loops, environmental impacts are reduced in two ways –by avoidance of both primary production through substitution by secondary materials and dissipation of potentially toxic and bioactive material into the environment; these two aspects are also referred to as the double dividend of a circular economy (Gößling-Reisemann and Gleich 2008).

To address the situation described above, detailed knowledge about the flows of metals and particularly their losses is required. Material flow analysis (MFA) can be considered the major tool to acquire

[1] End-of-life recycling rates describe the percentage of a metal in discard that is actually recycled (Graedel et al. 2011b). Different recycling rate definitions can be found in (Graedel et al. 2011b; Graedel et al. 2011a).

[2] "Technosphere" (also referred to as anthroposphere, societal subsystem, socio-technical or socio-economic subsystem) describes the subsystem that contains the stocks and flows mainly controlled by humans in contrast to the environmental subsystem which is sometimes also referred to as biosphere (see van der Voet 2002).

[3] At least given today's situation with significant environmental impacts in mining and a lack of recycling, mining of metals can be considered unsustainable –even for metals such as iron (reported end-of-life recycling rates between 52 and 90 %; Graedel et al. 2011a), copper (reported end-of-life recycling rates between 43 and 53 %; Graedel et al. 2011a) and aluminum (reported end-of-life recycling rates between 42 and 70 %; Graedel et al. 2011a). A complete (i.e. 100 %) recycling and reduced environmental impacts in primary production might alter this statement.

this knowledge. A recent review of MFA studies showed, however, that only few studies dealing with critical metals such as REE, germanium, indium, or gallium have been conducted so far, and –to the author's knowledge– hardly any studies analyzing dissipative material losses along the life cycle of single products in detail are among them.

Knowledge about dissipative losses is of particularly great value from a resource conservation standpoint (see for example Lifset et al. 2012). By tracking and quantifying material flows and (dissipative) losses the (in terms of material losses) most relevant stages along the product life cycle can be identified and visualized. Based on this, knowledge on "hot spots" or "low hanging fruits" for optimizations of the metals' life cycle management can be obtained.

Further findings from MFA studies include knowledge about the (future) demand for the analyzed materials and quantifications of anthropogenic material stocks and secondary material flows. In addition, such analyses may contribute to more accurate calculations of recycling rates (e.g., Lifset et al. 2012). Where "hot spots" in terms of leakages to the environment are identified, more narrowly focused studies on –for example– exposition and toxicity may be performed. Knowledge about the amounts and whereabouts of metals further contributes to the question of future landfill, urban or technosphere mining (*"Where to look in the future for more metal [should new metal become costly]?",* Lifset et al. 2002) as described for example by Jones et al. (2013), Quaghebeur et al. (2013) or Johansson et al. (2012). Also, assessing prospective material flows allows conclusions regarding the future composition of waste streams and probable challenges for waste management. This applies especially to products that are relatively new in the technosphere, therefore currently showing a significant stock building, but only a very limited amount already reaching the end-of-life stage.

Contributing to this, in this thesis, the flows of critical metals along the life cycle of selected products are analyzed with a special focus on dissipative losses. The analyzed products and critical metals, respectively, are CIGS (copper-indium-gallium-diselenide) photovoltaic cells (indium and gallium), thermal barrier coatings (TBC) for aircraft engines (yttrium) and polymerization catalysts in PET production (germanium). As said before, to the author's knowledge, comparable studies have so far not been conducted. In this context, certain methodological challenges are dealt with, including the proposal of a classification scheme for dissipative losses and its implementation into MFA methodology. The assessment focuses on the relative material losses along the life cycle, includes potential future changes, and a dynamic analysis of present and future absolute material stocks and flows is conducted. The focus of this dynamic MFA study is on products used in Germany (spatial scope) and the time horizon is 2030.

One main result of this analysis is detailed knowledge about the relative and absolute dissipative losses along the life cycle of the three case studies, including the current and future "where", "what kind" and "how much" of dissipative losses that can –as said before– serve as a basis for target oriented optimizations within the product life cycle as well as a data base for more comprehensive studies of the analyzed critical metals (i.e., for studies with a wider geographic scope and/or of additional

products) as well as for future studies on landfill and urban mining potentials and optimizations of waste management systems. In addition, the detailed description of the refined MFA approach may facilitate similar studies in the future. Furthermore, through the quantification of future material demands and secondary material flows resulting from the analyzed products a valuable contribution to identifying potential material shortages and upcoming challenges for waste management and recycling systems is provided.

Against this background, the thesis is organized in the following chapters. In chapter 2 the background and context of the overall objectives are described. Besides the role metals play in our society in general, the issue of resource criticality is looked into in detail. Here, such materials that are frequently considered to be “critical” are identified. Also a brief overview of literature dealing with material cycles is given and the core elements of a sustainable material management are described. Subsequently, in chapter 3 the state of research regarding dissipation of matter and its consideration in MFA studies is looked at and –based on this– a classification scheme for dissipative losses considering the location of occurrence and the receiving media to be applied in the analyses of the case studies is described. In doing so, an existing lack in consistency of nomenclature regarding material dissipation is addressed, too.

In chapter 4 the methodological approach used for the product-centric analysis of the case studies is described. The methodological approach builds on the established method of material flow analysis which is refined especially regarding the consideration of dissipative losses and the quantification of future material flows using lifespan distributions. In the dynamic assessment, lifespan distributions will be used instead of average lifespans where appropriate. The lifespan is an essential parameter in the analysis of dynamic systems (e.g., Murakami et al. 2010) and using a distribution instead of mean values can be considered a significantly more accurate approach in many cases (Murakami et al. 2010; Nomura 2005; Law 2007). In chapter 5 the analysis of the case studies is performed. In chapter 6 conclusions are drawn and an outlook is presented.

2 BACKGROUND OF THE STUDY

Germany's economy –just like the economies of all industrialized countries– is highly dependent on a variety of metals. Overall, global metal extraction and use increased over 19-fold from 1900 to 2005, basically covering traditional mass metals like copper, iron and aluminum that have been used already centuries ago (aluminum demand for example increased over 1,000-fold in the mentioned time span; Graedel et al. 2012). However, growth of population, new lifestyles, technological and regulatory changes, among other factors has altered the resource base of our society. Metals such as REE, indium, gallium, germanium, the platinum group metals (PGM) and others are of rapidly growing importance for them being used in all kinds of high-tech products. While brilliance, good electrical and heat conductivity, high strength, hardness and toughness as well as good plastic formability can be considered as the most important properties of the "traditional" metals (Gleich 2006), the before mentioned "emerging" metals have additional properties like heat resistance, electrical, magnetic and catalytic behavior among many others providing products with various new functionalities.

The increase in demand for these "emerging" metals in the past decades and particularly in the past five to ten years is particularly resulting from a variety of high-tech and future technologies, especially from so-called "green technologies" that are supposed to enable sustainability. Wind energy converters, photovoltaic cells, fuel cells, special coatings and alloys, electric cars or LEDs among other technologies, are an integral part of most conversion strategies towards a low-carbon society. An exemplary selection of technologies requiring such metals is shown in Table 1. Within these technologies, the mentioned metals are essential to achieve certain novel or significantly improved functionalities; therefore they are often also referred to as "high-tech" or "specialty" metals.

Table 1: Exemplary selection of technologies requiring critical metals (compiled from various sources; Reuter et al. 2013; European Commission 2010; Angerer et al. 2009; Buchert, Schüler, and Bleher 2009)

Technology	Required critical metals
Wind energy converters	Nd, Dy, Tb, Pr
Photovoltaics	Cu, In, Se, Ga, As, Cd, Ge, Si, Sn, Pt
Fuel cells	Pt, Au, Pd, Y
Electric, hybrid and fuel cell cars	Li, Sn, In
LEDs	Ga, As, In, Zn, Se, W
Catalysts	Pt, Pd, La, Ce, Ge
Microelectronics	Ag, Bi, Au, Re, Ag, Ga, Cd, Te
Optical fiber applications	Ge, Er
Special ceramics	Y, Ce

In addition to their growing importance, these materials often show a high supply risk, i.e. a relatively high likeliness of supply interruptions. The combination of these two dimensions –high importance and high supply risk– is also referred to as criticality. This aspect is looked at in detail in section 2.1.

With technological progress, a progressive use of elements from almost the entire periodic table within the past few decades can be observed (see Figure 1). The shift in the variety of metal-use is well documented and described in various studies (cf. National Research Council 2007; Erdmann and Behrendt 2011; Erdmann and Graedel 2011; Angerer et al. 2009). In the respective technologies, critical metals are used in their majority in relatively small and –due to growing efficiency– further shrinking quantities regarding the single product. Still, because of the overall increasing demand for these technologies, the absolute demand for these metals is constantly growing. The rate in which critical metals are being extracted from the lithosphere has increased in excess of about 3 % per year for more than 50 years (Gordon, Bertram, and Graedel 2006). Even further increases are likely to be expected for the future (see for example Angerer et al. 2009; Moss et al. 2011; Erdmann and Behrendt 2011). The necessity of reducing extraction rates especially for critical metals in order to ensure a sustainable metals supply has just recently been highlighted by Henckens, Driessen, and Worrell (2014), though.

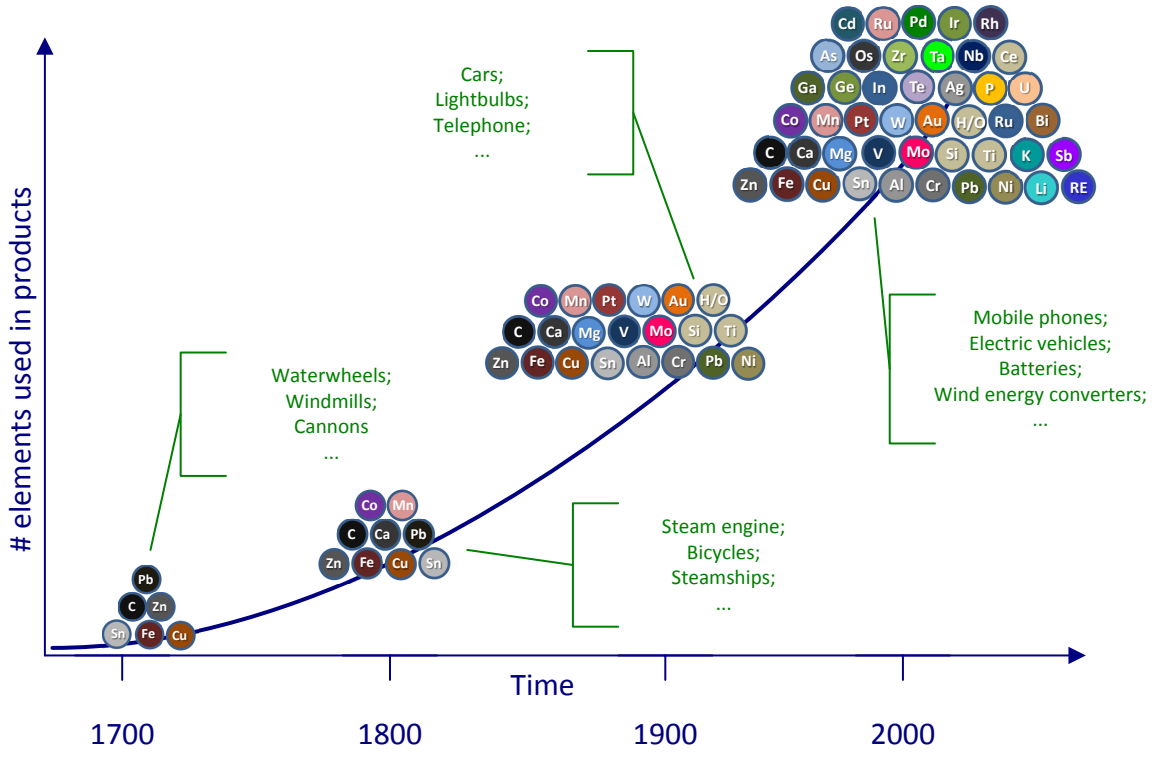

Figure 1: Increase in variety of metal use (adapted from Reuter et al. 2013)

In public awareness, the described development is reflected only with quite some delay. While the dependency on energy resources like crude oil, natural gas, lignite, and hard coal has become quite evident during the oil crisis of 1973 and is within public attention ever since, the dependency on various rare metals is an issue that attracted only little attention for a long time and has been discussed exclusively among few experts (cf. Erdmann and Behrendt 2011). A few years ago, however, a shift in the public awareness could be observed. Especially the Chinese policy of limiting the export of rare earth elements acted like a trigger for raising public awareness about the issue of scarce and critical metals. A shift could also be observed in studies on the importance and availability or supply situa-

tion of metals, i.e. in studies on the criticality of metals. While older studies have a much stronger focus on "traditional" metals like copper, aluminum, or tin (e.g., Frondel et al. 2006), newer studies pay a lot more attention to high-tech metals like REE, indium, gallium or PGM (e.g. European Commission 2014a; American Physical Society and Materials Research Society 2011; Erdmann and Behrendt 2011; European Commission 2010; Buchert, Schüler, and Bleher 2009).

2.1 Criticality of Materials

Criticality is a concept used for the assessment of materials motivated by the growing importance of all kinds of high-tech and future technologies that require not only a couple of common materials like steel, aluminum, or copper but almost the entire periodic table of elements as it has been described above. Triggered by events like export restrictions for REE in China, the issue of criticality is frequently dealt with in various studies since a couple of years (see Table 3 for an overview of criticality studies). Still, also in older publications the term "critical" can be found for bottleneck materials or materials particularly vulnerable to supply restrictions (e.g., Ayres 1999).

Nowadays, criticality is commonly assessed as the risk or likelihood of an interruption of supply combined with the resource consuming system's (i.e., a state's, economy's, sector's, etc.) vulnerability[4] to supply shortages, often assessed as the material's economic or technological importance as a measure for the impacts of supply shortages. Most criticality assessments agree on these two main dimensions even though they differ in the criteria and concepts used to assess them as well as in their geographic, technological scopes and time horizons. Accordingly, definitions for criticality do not differ much, e.g.:

- "A *raw material is labeled 'critical' when the risks of supply shortage and their impacts on the economy are higher compared with most of the other raw materials.*" (European Commission 2010)
- *"To be critical, a mineral[5] must be both essential in use […] and subject to supply restriction […]."*(National Research Council 2007)

The two dimensions are usually assessed using geological, technical, environmental, social, political and economic criteria. The geological criteria cover aspects like the amount of reserves and resources among others to assess the physical material availability. The technical criteria include as-

[4] Although in criticality assessments "vulnerability" is commonly implicitly understood as "the potential damage to resource consuming systems", strictly speaking, the concept of vulnerability has a much broader meaning in science. Turner et al. (2003), for example, define vulnerability as "*the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor*". It is defined as a function of exposure, sensitivity, and the system's adaptive capacity (Gößling-Reisemann et al. 2013; Turner et al. 2003). In this thesis, though, the term "vulnerability" will be used in accordance with its use in criticality studies.

[5] While some criticality studies refer to materials, others refer to more generic terms such as minerals (a naturally occurring substance formed by geological processes). In the actual criticality assessments, almost all studies look at single elements, though.

pects like the substitutability, recyclability, and the material efficiency potential, assessing present and future influence of technical influences with impact on supply risk and consequences of supply shortages. Questions about the material being produced in an environmentally and socially accepted way are covered within the environmental and social criteria (cf. National Research Council 2007). The political criteria assess the potential (or foreseeable) influence of governmental actions and policies on the supply situation, and the economic criteria consider the economic importance, macro and micro economic figures with influence on the mentioned supply risk and consequences. As an example, the criteria used in a criticality assessment for Germany by Erdmann and Behrendt (2011) are shown in Table 2.

Table 2: Criteria to assess vulnerability and supply risk in (Erdmann and Behrendt 2011)

Vulnerability / economic importance	**Supply risk**
Germany's share on world demand	Country risks for imports
Dynamics of Germany's share on world demand 2004 to 2008	Country risks for global production
Dynamics of imports to Germany	Country concentration of reserves
Sensitivity of value chain in Germany	Company concentration of production
Global demand impulse from future technologies (2030)	Ration of global reserves to global production
Substitutability	Share of global main and co-production
	Recyclability

Many of the criteria cannot be unambiguously assigned to one of the categories, though; substitutability for example is assigned to the dimension "supply risks" in a criticality study conducted on behalf of the European Commission (European Commission 2010), while it is assigned to the dimension "impact of supply restrictions" in a study conducted by the US National Research Council (National Research Council 2007). In some assessments environmental implications are added as a third dimension (e.g., Graedel et al. 2012), while they are included in the supply risk in other assessments.

A review of recently published criticality assessments (with regard to the 2011 review done by Erdmann and Graedel (2011)) also shows that the concept of criticality is dynamic, subjective and specific as well as relative. It is dynamic because the criticality of a material can change over time –by changes within the values of the underlying criteria. It is for example possible that the supply situation changes by mines being closed or (re-) opened like it is expected for rare earth elements in the next few years. The general importance of a material may increase or decrease, too. Some criteria also have a natural fluctuation over time like it is the case for the price which is subject to the raw material cycle[6] (cf. Reuscher et al. 2008). Also, the time horizon chosen in the respective criticality assessment is of relevance for the results.

[6] Within criticality assessments, the price is often used as an indicator for a materials scarcity. However, raw material prices are usually developing cyclically: Additional capacities are built up when the prices are high which can lead to an oversupply and a decline in prices which then again leads to the closing of mines that are

Furthermore, criticality is subjective and specific because it assesses materials based on individual goals and scopes for a particular resource consuming system. The criteria applied within these assessments are often weighted based on the author's judgment (Erdmann and Graedel 2011). Within a criticality assessment materials are not considered "critical" in general but only for the specific system the assessment has been carried out for. This can be a political union like the EU (European Commission 2010), a country like the US (National Research Council 2007) or Germany (Erdmann and Behrendt 2011) or a single federal state like Bavaria (Reller 2009). Some assessments focus on a single industry sector or branch, too; so far mainly on the energy sector (Achzet et al. 2011; American Physical Society and Materials Research Society 2011; Moss et al. 2011) or so-called sustainable technologies (Buchert, Schüler, and Bleher 2009). Evidently, this potentially causes differences in the results of the assessments.

Finally, criticality is a relative concept since it compares different materials to each other. For a stand-alone material, making conclusions about its criticality is not straightforward (unless threshold values for both dimensions are defined without consideration of other materials). Criticality is usually determined in comparison to other materials, e.g., a relatively higher supply risk and relatively higher consequences of a supply shortage lead to a material being considered as critical. Here, an additional influencing factor is the initial selection of materials. Usually not each element from the entire periodic table is included in the assessments affecting the outcomes of such assessments, too.

Additional factors influencing the results of criticality assessments are mentioned by Erdmann and Graedel (2011). They particularly highlight the importance of methodological aspects like the applied method of assessing the impact of supply disruptions, materials' substitutability, and –if applied– the applied methods for aggregation to a criticality index[7]. The methodological differences as well as the issue of criticality being dynamic, subjective, and specific as well as relative, emphasize that materials cannot be considered to be critical in general. This means, a general list of "critical metals" does not exist. However, there are certain similarities within the different criticality assessments. Some metals like the REE, indium or the PGM are considered critical in a significant part of the studies. Against this background, the results from a review of 16 studies assessing materials' criticality are presented in the following and "common critical materials" are identified. The list of these metals is taken into account in the selection of the case studies (see chapter 5). Since the focus of this work lies on metals, non-metals are not considered in this comparison[8].

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no longer profitable or declining investments. The reduced supply can then again lead to increasing prices. This raw material cycle can last –depending on the respective material– around 30 years (Reuscher et al. 2008).

[7] Regarding the aggregation to a criticality index it has to be added that there are basically three different concepts to assess criticality (Erdmann and Behrendt 2011): The matrix concept where risk and vulnerability are separate dimensions, the index concept which is highly aggregated, and the disaggregated multi-indicator concept. Among these, the matrix concept is the most commonly applied one.

[8] Metalloids (e.g., germanium, tellurium, antimony), however, are included in the assessment and no differentiation between metals and metalloids is made. A metalloid is an element with properties in between those of metals and non-metals.

For the comparison, studies not older than from 2007 have been used. They have been identified by literature and internet search. The selected studies either focus explicitly on criticality according to the above description or implicitly deal with the same subject without labeling it as such. The considered studies are shown in Table 3.

Table 3: Studies considered in the comparison of criticality assessments

Achzet, B., Reller, Armin, Zepf, Volker, Rennie, C., Ashfield, M., and Simmons, J. "Materials critical to the energy industry: An introduction." 2011.
American Physical Society, and Materials Research Society. "Energy Critical Elements: Securing Materials for Emerging Technologies." A report by the APS panel on public affairs & the materials research society, 2011.
Buchert, Matthias, Schüler, Doris, and Bleher, Daniel. "Critical Metals for Future Sustainable Technologies and their Recycling Potential." 2009.
Duclos, Steven, Otto, Jeffrey, and Konitzer, Douglas. "Design in an Era of Constrained Resources." *Mechanical Engineering* 9, no. 132 (2010): 36–40.
Erdmann, Lorenz, and Behrendt, Siegfried. "Critical raw materials for Germany"[9] Final report, 2011.
European Commission. "Critical raw materials for the EU." Report of the Ad-hoc Working Group on defining critical raw materials, 2010.
European Commission. "Critical raw materials for the EU." Report of the Ad-hoc Working Group on defining critical raw materials, 2014. – Update of 2010 study.
Frondel, Manuel, Angerer, Gerhard, Buchholz, Peter, Grösche, Peter, Huchtemann, Dirk, Oberheitmann, Andreas, Peters, Jörg, Sartorius, Christian, Röhling, Simone, and Wagner, Markus. "Trends of supply and demand situation for mineralic raw materials."[10] Final report, 2006.
Hatch, Gareth. "Critical Rare Earths: Global supply & demand projections and the leading contenders for new sources of supply." 2011.
Morley, Nick, and Eatherley, Dan. "Material Security: Ensuring resource availability for the UK economy." Strategic report produced by the Resource Efficiency Knowledge Transfer Network, 2008.
Moss, R. L., Tzimas, E., Kara, H., and Kooroshy, J. "Critical Metals in Strategic Energy Technologies: Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies." JRC Scientific and technical reports, 2011.
National Research Council. "Minerals, Critical Minerals and the U.S. Economy." Prepublication Version, 2007.
OECD. "Material Case Study 1: Critical Metals and Mobile Devices." Working Document, 2010.
Reller, Armin et al. "Raw material situation Bavaria: No future without raw materials"[11] 2009.
Thomason, James, Atwell, Robert, Bajraktari, Ylli, Bell, James, Barnett, Sean, Karvonides, Nicholas, Niles, Michael, and Schwartz, Eleanor. "From National Defense Stockpile (NDS) to Strategic Materials Security Program (SMSP): Evidence and Analytic Support." Volume I, 2010.
U.S. Department of Energy. "Critical Materials Strategy." US DOE report, 2012, accessed January 2012.

The listed studies are compared to identify metals that are commonly considered critical. However, also other aspects like the year in which the study was published, the geographical, time and technological or economic scope and the aggregation method have been included in the assessment. Some of the studies have already been included in a previous review performed by Erdmann and Graedel (2011) where similar categories are assessed but some additional studies are included here, as well. The most relevant category within the comparison is, of course, the actual results in terms of the

[9] In German; original title: "Kritische Rohstoffe für Deutschland: Identifikation aus Sicht deutscher Unternehmen wirtschaftlich bedeutsamer mineralischer Rohstoffe, deren Versorgungslage sich mittel- bis langfristig als kritisch erweisen könnte."

[10] In German; original title: "Trends der Angebots- und Nachfragesituation bei mineralischen Rohstoffen."

[11] In German; original title: „Rohstoffsituation Bayern: Keine Zukunft ohne Rohstoffe: Strategien und Handlungsoptionen."

metals that are considered as critical. Based on this, the number of “criticality-considerations” is determined later on, i.e. the number of studies that consider a particular metal as critical. Here, it has to be noted that some studies distinguish between different types of criticality; the differentiations include different time horizons like short-, mid- and long-term criticality (see for example Buchert, Schüler, and Bleher 2009) and different degrees of criticality like very high, high, medium etc. (e.g., Erdmann and Behrendt 2011). In these cases it had to be decided which metals to count for the comparison. Regarding the different time horizons, no differentiation was considered, meaning that metals that have been identified to be critical in one or more different time scales within one study are counted once. It can be noted, though, that there is no universal understanding of short-, mid-, and long-term in the different criticality studies (see Table 4). Regarding the degree of criticality, the results of the different studies have been compared, and based on the methodological approach in the other studies it has been decided whether or not they are to be included. The decisions which metals have been included are shown in Table 4. In addition, the influence of including all elements considered being of low, medium, or high criticality is analyzed below.

Another difference between the studies is that in some studies REE and PGM are analyzed individually, while in other studies they are analyzed as a group. To address this, they are considered as one group each in the first step, while more detailed analyses that look at the individual metals are carried out in a second step. At first, each of the studies considering one or more particular REE or PGM as critical is treated as if it considered the respective metal group. The following overview (Table 4) shows the results from the comparison of the considered studies.

Table 4: Comparison of criticality assessments

Institution & Reference	Year of study	Geographical Scope	Time horizon	Aggregation method	Technological/ economic Scope	Metals considered to be critical
BP: Achzet et al. 2011	2011	global	not defined	two dimensions	energy sector	Cd, Co, Ga, Ge, Pt, REE, Rh, Te, U *(all taken into account for # of criticality-considerations)*
APS: American Physical Society and Materials Research Society 2011	2011	USA	"current situation" (approximately 2010/2011)	multiple indicators	Energy technologies	Li, Sc, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Yb, Lu, Re, Ru, Os, Co, Rh, Ir, Pd, Pt, Ag, Ga, In, Ge, Se, Te *(all taken into account for # of criticality-considerations)*
Öko-Institut: Buchert, Schüler, and Bleher 2009	2011	global	short term (<5 years), mid-term (till 2020), long-term (till 2050)	Criticality matrix, three dimensions	Future sustainable technologies	Short-term: Te, In, Ga mid-term: REE, Li, Ta, Pd, Pt, Ru long-term: Ge, Co *(all taken into account for # of criticality-considerations)*
GE: Duclos, Otto, and Konitzer 2010	2010	GE	not defined	Criticality matrix, two dimensions	GE material demand	RE + six other materials (results not available) *(all taken into account for # of criticality-considerations)*
kfw: Erdmann and Behrendt 2011	2011	Germany	short term (<5 years), mid-term (5-10 years), long term (10-20 years)	criticality matrix, two dimensions	Future technologies	very high criticality: Ge, Rh, Sb high criticality: W, REE, Ga, Pd, Ag, Sn, In, Ni, Cr, Bi *(high and very high taken into account for # of criticality-considerations)* (medium criticality: Te, Pt, Cu, Li, Be, Co, V, Ni, Hf, Zn, Mo, Sr, Se)
EC: European Commission 2010	2010	EU	10 years	criticality matrix, two dimensions (+environmental aspects)	Economy, implicit focus on future technologies	Sb, Be, Co, Ga, Ge, In, Mg, Mn, Nb, PGM, REE, Ta, W *(all taken into account for # of criticality-considerations)*
EC: European Commission 2014b	2014	EU	(implicitly) 10 years (approach in accordance with 2010 study)	criticality matrix, two dimensions	Economy, implicit focus on future technologies	Sb, Be, Cr, Co, Ga, Ge, In, Magnesite, Mg, Nb, PGMs, heavy REE, light REE, W
RWI: Frondel et	2006	Germany	2025	multiple indica-	Economy	Cu, Zn, Ge, Pt

al. 2006				tors		*(all taken into account for # of criticality-considerations)*
TMR: Hatch 2011	2011	Global	2010-2017	one dimension (supply)	Future technologies using RE (implicit)	Dy, Y, Te, Eu, Nd *(all taken into account for # of criticality-considerations)*
Oakdene Hollins: Morley and Eatherley 2008	2008	UK	long term (not specified)	Criticality index	Economy	Au, Rh, Pt, Sr, Ag, Sb, Sn *(all taken into account for # of criticality-considerations)*
JRC: Moss et al. 2011	2011	EU	2020, 2030	multiple criteria	Low-Carbon Technologies	high: Nd, Dy, Te, Ga, In medium: Nb, V, Sn, Se; *(high and medium risk taken into account into account for # of criticality-considerations)* (low risk: Ag, Mo, Hf, Ni, Cd)
NRC: National Research Council 2007	2008	USA	<10 years	criticality matrix, two dimensions	Economy	Mn, In, Nb, Rh, Pt, REE (Ga, Pd close to be critical; *not considered for criticality-counts*)
OECD: OECD 2010	2010	Global	not defined	criticality matrix, two dimensions	Mobile devices	(Sb, Be, Pd, Pt – not explicitly) *(not taken into account for # of criticality-considerations)*
IW Consult: Reller 2009	2009	Bavaria	not defined	Criticality index	Economy	Y, Nd, Co, Sc, W, Ni, Se, Ge, PGM, Li, Cr, In, Mb *(all taken into account for # of criticality-considerations)*
IDA: Thomason et al. 2010	2010	USA	conflict year plus 3 years	Scenarios for supply and demand	Defense sector	68 materials, u.a. Eu, Te, Nd, Li; also goods like kevlar, glas fibre, steels *(not taken into account for # of criticality-considerations)*
US DOE: U.S. Department of Energy 2011	2012	USA	short-term (-2015) and mid-term (2015-2025)	Criticality matrix, two dimensions	Clean energy technologies	short-term: Dy, Tb, Eu, Nd, Y; (near-critical: Ce, In, La, Te) mid-term: Dy, Nd, Eu, Y, Tb (near critical: Li, Te) *(both taken into account for # of criticality-considerations, near-critical not taken into account)*

The first two columns show the responsible institution behind the study, the respective reference and the year in which the study was published. The following columns show the geographical scope, the time horizon of the study, the chosen aggregation method and the technological or economic scope that states whether the study focuses on a defined group of technologies, an economic sector or the economy as a whole. The last column presents the most relevant results of each study, i.e. the metals that are considered as critical. Based on this column the number of criticality-considerations is determined. The results from the comparison are shown in Figure 2. As it can be seen in the figure, the rare earths metals and the platinum group metals are the materials that are most frequently considered as critical. Due to their specific situation that they are treated as a group in some studies and as single materials in other studies as described above, they are discussed below separately in more detail. The following "particularly critical" metals are germanium and indium being considered as critical in 8 of the studies, followed by gallium (seven times) and tellurium and cobalt (six times).

In the evaluation, two of the analyzed studies were not taken into account at all. The OECD study (OECD 2010) does not explicitly label the mentioned materials as critical and has therefore not been considered for the criticality-considerations[12]. The IDA study (Thomason et al. 2010) looks at goods like Kevlar and glass fiber as well as at materials or metals which would mean an inconsistency within the comparison that is performed here. As stated above and noted in Table 4, materials identified to be of low or medium criticality have partially not been taken into account for the comparison based on the qualitative comparison of the different criticality studies. Including those excluded materials would, however, mean only marginal changes to the table. The REE, germanium, indium and gallium would remain unaltered, platinum (for being labeled as medium-critical in Erdmann and Behrendt 2011) and tellurium (for being labeled as near-critical in U.S. Department of Energy 2011 and medium-critical in Erdmann and Behrendt 2011) would move one or two places up, respectively.

[12] However, including the OECD study, would lead to no relevant changes to the results of the comparison: PGM would still be the second "most critical" material group, Sb and Be would move one place up.

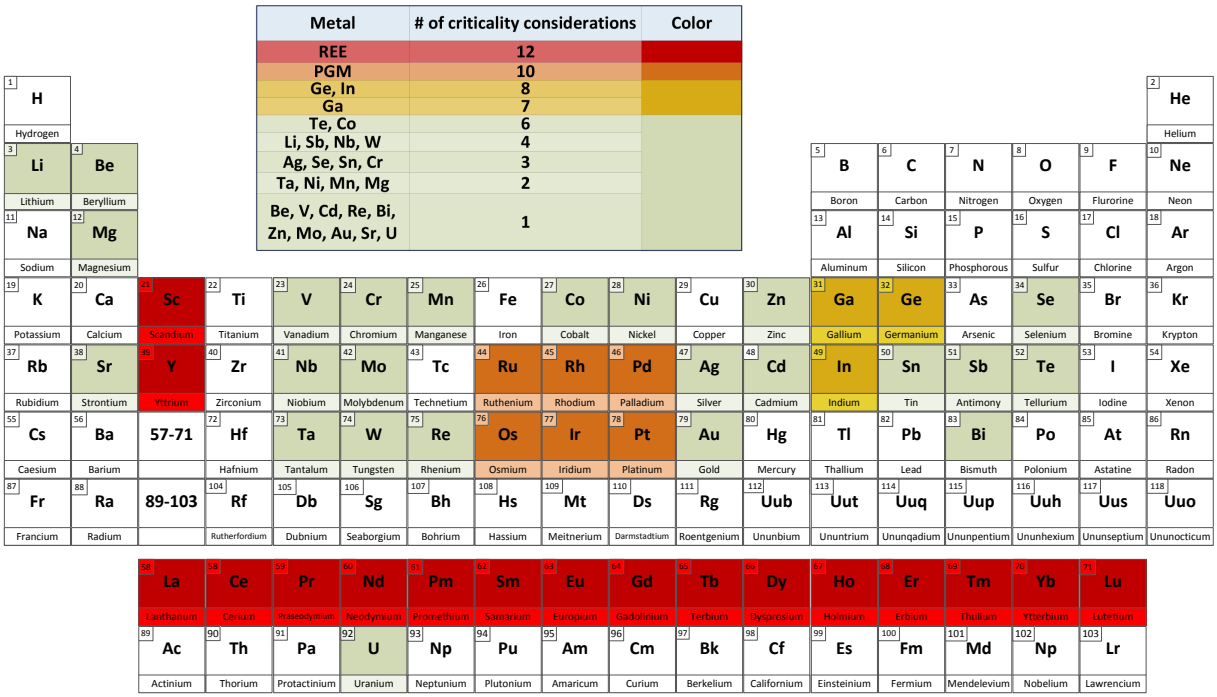


Figure 2: Metal criticality-considerations from 14 studies (own survey)

The rare earth elements as a group or one or more individually have been considered critical in eleven studies. Six studies differentiate between the individual rare earth metals, the European Commission (2014b) differentiates between light and heavy REE[13]. All of them consider neodymium to be critical, followed by yttrium, europium, and dysprosium that are considered to be critical in 4 studies. The following metals are terbium (three criticality-counts), scandium (two) and lanthanum, cerium, praseodymium, samarium, gadolinium, ytterbium and lutetium (one each). Promethium, holmium, erbium and thulium did not appear as critical among the assessed studies[14]. An overview of the results is given in Table 5.

Table 5: Criticality-considerations for Rare Earth Metals (own survey)

Criticality considerations	Metal
6	Nd
4	Y, Eu, Dy
3	Tb
2	Sc
1	La, Ce, Pr, Sm, Gd, Yb, Lu

Eleven of the assessed studies consider the PGM as a group or at least one PGM individually to be critical. Within eight studies the PGM are not regarded as one group but as individual metals. Within these, platinum is most frequently considered as critical (six times), followed by rhodium (five) and

[13] Here, heavy REE show a significantly higher supply risk than light REE but, still, both groups have higher supply risks than any other metal. See section 5.1.4 for a more detailed differentiation of both groups.

[14] Also a study by the German Federal Institute for Geosciences and Natural Resources (BGR) concludes that holmium, thulium and erbium are commonly not considered to be critical (Elsner 2011).

palladium (four). Ruthenium (two times), iridium and osmium (one each) are explicitly considered as critical only in few studies. An overview of these results is given in Table 6.

Table 6: Criticality-considerations of PGM (own survey)

Criticality considerations	Metal
6	Pt
5	Rh
3	Pd
2	Ru
1	Ir, Os

Based on these findings, it can be concluded that besides all methodological differences between criticality assessments, there are some elements that can be considered "common critical metals". These include the REE, the PGM, indium, gallium, and germanium. These "common critical metals" are taken into account in the selection of the case studies in chapter 5.

2.2 Studies on Flows and Losses of Critical Materials

The study of anthropogenic material flows or cycles is a main field of research within industrial ecology[15] and material flow analysis (MFA), i.e., the systematic assessment of flows and stocks of materials within a system defined in space and time (Brunner and Rechberger 2004), can be considered as the "*core tool*" (Ayres and Ayres 2002) in this context (cf. section 4.1). MFA aims at understanding the metabolism of the analyzed (industrial) system in terms of the exchange of matter and energy between system components and with the environment (see also Zimmermann and Gößling-Reisemann 2015). If flows in and out of natural and technological stocks are studied, this can also be called a balance while quantifications of flows into, out and among several stocks are called a cycle (cf. Harper 2008; Ayres and Ayres 2002). Dissipative losses can be assessed as part of MFA studies by different methodological approaches as described in chapter 3 and 4; however, only a minority of studies actually analyzes dissipative losses in detail (see section 3.2).

There are various specific types of MFA studies that differ depending on the respective purpose of the study. These methodological differences are looked at in more detail in chapter 4. One major difference lies in whether material flows are analyzed from a macro perspective or on product level. The major share of MFA studies is carried out on an aggregated level, i.e. they are material-centric and analyze material flows on a global, national, or geographic level, usually based on historical data. Examples for such studies can be found in (Reck et al. 2008) for nickel, in (Harper and Graedel 2008) for tungsten or (Rechberger and Graedel 2002) for copper. A broad review of publications on anthro-

[15] In industrial ecology, natural ecosystems are used as models for industrial activity (Lifset and Graedel 2002), see also chapter 4. The fundamental principles have already been described by Frosch and Gallopoulos (1989), detailed descriptions of the theoretic and methodological foundation of the field can be found, for example, in (Ayres and Ayres 2002) as well as in (Gleich and Gößling-Reisemann 2008) where also exemplary practical applications are presented.

pogenic elemental cycles has been published by Chen and Graedel (2012) covering about 350 publications containing over 1,000 anthropogenic elemental cycles. The majority of these cycles are found to be static, only 85 being dynamic, i.e. analyzing an elemental cycle over several intervals in time. 5 % of the studies are at global level and 80 % at country- or territory-level.

Analyses on a disaggregated product level are less common than material-centric studies. Such studies –with differences in their goals and scopes– have been carried out based on historical data for example by Harper (2008) for products containing tungsten, by Mathieux and Brissaud (2010) for aluminum in commercial vehicles, or by Elshkaki et al. (2005) who published a dynamic stock model for lead contained in cathode-ray tubes. An analysis of dissipative losses has not been conducted within these studies. Most studies –material- and product-centric– build on historical data and analyze material flows in the past while only few studies deal with potential future flows of materials.

In their review on anthropogenic material cycles Chen and Graedel show that such cycles exist for 30 elements, with iron being the most analyzed one with more than 200 analyses available followed by nickel, copper, lead, zinc, silver and chromium (Chen and Graedel 2012). The cycles of "common critical metals" like REE, indium, or gallium have been analyzed only in few studies that do not include a full material flow model (i.e. focusing on stocks or certain applications/final products or end-use sectors) or are limited to a certain geographic area (e.g., Shi et al. 2010, where dysprosium flows are assessed for Japan). A sufficient quantification of losses, however, cannot be found within these publications. Among the critical materials the platinum group metals appear to be the most studied. MFAs of PGM have, for example, been published by Hagelüken and colleagues (Hagelüken 2005; Hagelüken, Buchert, and Stahl 2005), and Saurat and Bringezu (2008; 2009). For the rare earth metals several studies assessing stocks and flows on a rather aggregated level have been published by Du and Graedel (2011a; 2011b; 2011c). Similar studies for other critical metals like indium, gallium, and tellurium have –to the author's knowledge– not yet been carried out.

The quantification of material losses during production, losses to the environment, rates of recycling and other aspects related to material dissipation can be done as part of material flow analyses (or metal cycles). In most MFAs, however, (dissipative) losses are not an (explicit) part of the scope or are not quantified but there are some existing studies that deal (explicitly or implicitly) with material dissipation. Dissipative losses on material level are for example assessed in studies on copper (Erdmann et al. 2004; Lifset et al. 2012; Ruhrberg 2005; Wittmer 2006), nickel (Eckelman, Reck, and Graedel 2012; Eckelman, Reck, and Graedel 2012) or silver (Eckelman and Graedel 2007).

Most of these studies, however, only consider dissipative losses into the environment and do not distinguish between different types of dissipation. Especially for critical materials, publications on dissipative losses can barely be found. These aspects will be reviewed in detail in chapter 3.

2.3 Sustainable Materials Management

As aforementioned, the outcomes of this thesis may be used to contribute to a development towards a more sustainable management of metals. Hence the concept of sustainable materials management[16] (SMM) is described in more detail in the following. In addition, key elements and recommendations of selected major political frameworks and strategies aiming at a more sustainable resource management are outlined.

SMM has been characterized especially by the Organization for Economic Cooperation and Development (OECD). Here, sustainable materials management is described as a policy approach that can contribute to green growth[17] (OECD 2012) and is further defined as "*an approach to promote sustainable materials use, integrating actions targeted at reducing negative environmental impacts and preserving natural capital throughout the life cycle of materials, taking into account economic efficiency and social equity*." (OECD 2012; OECD 2010). It is a life cycle wide approach comprising different stages such as material extraction and production, transportation, fabrication of products, consumption/use of products, and end-of-life including reuse, recovery, and final disposal. Since the life cycle of materials usually stretches across political and geographic borders and involves various economic actors, effectively addressing the life cycle wide environmental impacts is a key challenge in SMM (OECD 2012). Generally, it has to be noted that sustainability principally covers the triad of economic, social, and environmental aspects, which is also referred to as the triple bottom line (Elkington 2004) and as also indicated in the given OECD definition. Still, mostly SMM is understood as a concept first and foremost dealing with efficient material use, (short- and long-term) material availability, and environmental implications of material production, which is well in line with the objectives of this work. The necessity of applying an according focus in order to maintain applicability and possible ways to include social, economic, and additional environmental aspects are discussed elsewhere (e.g., Subramanian et al. 2014; Wigger, Zimmermann, and Pade 2015). Thus, SMM primarily concerns two dimensions, the sustainable supply of materials and the environmental implications of material use.

Sustainable material supply

The issue of sustainable supply can be further concretized by dividing into the issue of material extraction and the issue of existing deficits regarding a circular economy. A definition of sustainable metal extraction rates is given by Henckens, Driessen, and Worrell (2014) saying that "*[t]he extraction rate of a metal is sustainable, if […] a world population of 9 billion can be provided with that metal for a period of at least 1000 years […]"*. Without discussing this definition further, it can be said that obviously the sustainability of providing primary material depends on the extraction rates. The

[16] In studies focusing on metals, the term "sustainable metals management" is frequently used. While the term sustainable materials management is more generic, the focus in this thesis is on metals. Still, in accordance with the OECD definition, the term "sustainable materials management" will be used in the following.

[17] By the OECD, green growth is defined as "*fostering economic growth and development, while ensuring that natural assets continue to provide the resources and environmental services on which our well-being relies*" (OECD 2011).

demand for primary material is essentially influenced by the existence of open or closed loops for these materials. Possible deficits in material cycles include (see, e.g., Gleich 2006; Jackson, Lederwasch, and Giurco 2014)

- the depletion of global reserves / material scarcity;
- recycling rates / lack of recycling / high scale of material losses;
- (low) quality of recyclates; and
- occupational safety and health protection aspects.

Partly, these deficits are closely related to the issues addressed in criticality assessments. All of these aspects (maybe health and safety only with some limitations) can be addressed by a transition from the currently still widely established linear models of consumption and production to circular models of resource use (Jackson, Lederwasch, and Giurco 2014) showing a close relation to the field of industrial ecology (cf. Frosch and Gallopoulos 1989) which is described in more detail in section 4.1. In a circular economy SMM is achieved through closed material loops which are free of quantity and quality losses (i.e. without dissipative losses and a highest quality recycling)[18] as well as consideration of material scarcities and the use of more abundant materials (OECD 2012; Gleich 2006).

Thus, optimization of recycling of entire products at their end-of-life and avoidance of dissipative losses is a core element of a circular economy and SMM, respectively. In this endeavor, Jackson, Lederwasch, and Giurco (2014) emphasize the importance of product-centric approaches that are better suited for respective optimizations (e.g., product oriented policy making) than material-centric approaches.

Environmental implications of material use

The other dimension of SMM, the environmental implications of material use, is often only discussed alongside without being in the focus of SMM strategies. Still, generally all phases of a material's life cycle are connected with environmental impacts which need to be reduced in order to stay within the planetary boundaries (Steffen et al. 2015; Rockström et al. 2009). I.e., material use can be considered environmentally sustainable as its impact on the nature is acceptable with consideration of the planetary boundaries (Steffen et al. 2015; Kral, Kellner, and Brunner 2013). Relevant impacts along a material's life cycle may include climate change, change in biosphere integrity, ozone depletion, ocean acidification, land-system change, and freshwater use (cf. Steffen et al. 2015). These "ex-

[18] It has to be noted that an increase in quantity and quality of recycling results in an increased energy demand. Rombach (2003; 2006), for example, analyzed the increases in primary energy demand resulting from an increase of aluminum recycling rates. While there is a net energy saving until some point (with consideration of energy savings from substituted primary metal), increasing recycling rates beyond that point increases the total demand for primary energy. Although detailed studies of such "optimal recycling rates" have not been conducted for critical metals so far (and besides the studies conducted by Rombach neither for other metals), one needs to keep this in mind when talking about a circular economy. Thus, material loops which are free of quantity and quality losses are more a theoretical idea and are not necessarily more sustainable than "almost closed loops".

ternalities" of material use are often particularly associated with the material production stage, but also with transportation and the product use phase (Fiksel 2006).

Strategies for a sustainable materials management

Various strategies for a development towards a sustainable materials management have been outlined by the scientific community (e.g., van Calster 2014; Fiksel 2006; Gleich 2006) as well as public authorities such as the European Commission (European Commission 2003; European Commission 2011; European Commission 2014c) or the German ministry for the environment (BMU 2012). Although many of these strategy papers differ in their goals and scopes, the outlined elements of a sustainable materials management are the same for the most part. While, for example, particularly scientific papers but also to some extent the German resource efficiency program (ProgRess, BMU 2012) highlight environmental sustainability as the major goal, the European Commission (2014c) emphasizes potential economic and growth effects as well as competitive advantages.

The key element of all SMM strategies is –as aforementioned– a development towards a circular economy. As described, in a circular economy material loops or cycles, respectively, are free of quantity and quality losses, i.e., there is highest quality recycling and no dissipative losses occur (OECD 2012; Gleich 2006). SMM strategies described various measures to achieve this, however, mainly on a rather general level and never product-specific. Measures to increase recycling and promote the closed-loop management of materials include (European Commission 2014c; van Calster 2014; BMU 2012; European Commission 2011)

- employing eco-design and design-for-recycling approaches;
- incentivize consumer behavior (regarding proper disposal of products);
- support industrial symbiosis approaches (financially and regulatory);
- limit energy recovery (incineration) to non-recyclable materials;
- phase-out landfilling;
- material substitutions (by materials that are better recyclable);
- environmental tax reforms that incentivize recycling for industry;
- defining waste treatment and recycling targets;
- promote markets for high quality secondary materials;
- increase producer responsibility;
- prevent illegal exports of waste products (particularly waste electrical and electronic equipment and end-of-life vehicles); and
- develop more efficient recycling processes, particularly for critical metals.

Besides the management of materials in a closed-loop, i.e., in a circular economy, there are various other elements that can be found in SMM strategies, a lot of which can be summarized as dematerialization. Dematerialization is also often discussed explicitly in SMM strategies (e.g., Angrick, Burger, and Lehmann 2014; Weizsäcker et al. 2009; Fiksel 2006). Quite generally it describes the reduction of the amount of material required to provide a certain function. Closely related to the concept of de-

materialization is that of material efficiency. In a narrow sense, material efficiency means “providing material services with less material production and processing”, while sometimes a broader understanding can be found, including aspects of recycling and environmental impacts, too (Wigger, Zimmermann, and Pade 2015). Both, dematerialization and material efficiency, can be achieved by various measures including (European Commission 2014c; BMU 2012; Allwood et al. 2011; Fiksel 2006)

- the increase of material efficiency in supply chains, thus reducing waste;
- the eco-design of products to reduce mass (i.e., light-weighting), packaging, life cycle energy requirements;
- the increase of durability (i.e., lengthening product lifespans) including modularization and component re-use;
- the reduction of transport;
- the promotion of new market models such as share-economy or other collaborative consumption models; and
- the reduction of subsidies which incentivize increased resource use.

Regarding dematerialization it needs to be considered, this it is not always automatically sustainable, as there are technological paths (e.g., renewable energies) that might be more material intensive than established paths but still allow for a more sustainable development in the long term (Fiksel 2006).

3 DISSIPATION OF MATTER

As it has been laid out, reducing dissipative losses of resources is an integral part of a sustainable materials management. Although the terms "dissipation" and "dissipative losses" are routinely used when talking about material life cycles and material management, there is by far no consistent understanding of the terms. As pointed out by Lifset et al. (2012) "*[c]onsensus about nomenclature is yet to emerge*". Addressing this, to start with, a brief introduction into the subject of dissipation of matter is given before a quantification of dissipative losses of selected critical metals (section 3.1) and an overview of MFA studies quantifying dissipative losses (section 3.2) is given. Afterwards, the nomenclature regarding dissipation from these studies is discussed (section 3.3) before a definition and a classification scheme for dissipative losses are presented (section 3.4).

Generally, in thermodynamics, dissipation is an aspect of an irreversible process in which available energy is transformed to unavailable energy, hereby producing entropy. These thermodynamic principles can also be applied to matter[19]. Just like energy, matter exists between two extremes, available and unavailable and "*it degrades continuously and irrevocably from the former to the latter state*" (Georgescu-Roegen 1986). However, Georgescu-Roegen (1986) admits that various authors argue that all matter can be recycled given sufficient available energy.

The losses can occur along the entire life cycle of a material (see Figure 3). Dissipative losses from the use phase are for example rust and wear and tear of motors and automobile tires. Other illustrative applications leading to dissipation of matter are pesticides, animal feeds, fertilizers, fireworks, or fuels additives (Ayres and Simonis 1994; Lifset et al. 2012). While these are explicitly dissipative applications, for many other applications dissipation happens most at the end-of-life. Ayres and Simonis (1994) point out that "*in thermodynamic terms there are only two possible fates for waste materials: recycling/reuse or dissipative loss*"[20].

[19] The concept of entropy has for example been applied to measure resource use or consumption, respectively, by Rechberger (Rechberger and Graedel 2002; Rechberger and Brunner 2002; Sobańtka, Zessner, and Rechberger 2012) and Gößling-Reisemann (Gößling-Reisemann 2008a; Gößling-Reisemann 2008b).

[20] While this statement is true for technological systems and typical socio-economic timeframes, it is not unconditionally valid for natural cycles like the carbon cycle and geological timeframes.

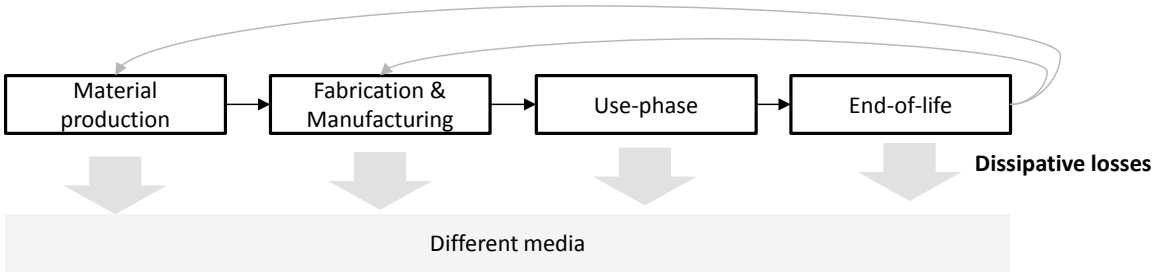


Figure 3: Dissipative losses along the life cycle

While some authors emphasize the potential of metals for almost infinite recovery and reuse[21] (cf. Gordon, Bertram, and Graedel 2006; Gleich 2006; Wernick and Themelis 1998), it can be said that various socio-economic and technical factors set a practical limit to this theoretically unlimited cycling of metals in the technosphere (Ayres 1999). Some authors (e.g., Georgescu-Roegen 1986) even state that perfect (i.e. 100%) recycling is "*categorically impossible*" due to dissipation – comparable to the transformation of energy and the second law of thermodynamics. This is widely argued, though (see e.g., Ayres 1999; Bianciardi, Tiezzi, and Ulgiati 1993), and the natural carbon, nitrogen, and oxygen cycles are given as counter examples. It is said that unless solar or other energy becomes unavailable all chemical elements and many organic substances can be accumulated by living systems from background crustal or oceanic concentrations without limits (Ayres 1998); i.e., the question of closing material cycles is also one of energy demand and availability as already discussed in section 2.3.

A first indication of the scale of dissipative material losses can be obtained from material recycling rates. A look at the work done by Graedel et al. (2011a; 2011b) indicates that, especially for critical metals, dissipation occurs on a rather high scale leading to a large share of these materials becoming unavailable. For example, EOL recycling rates for some of the "common critical metals", namely germanium, indium, gallium, and REE, are below one percent indicating an almost complete loss of these materials at product end-of-life. Already in 1986, Georgescu-Roegen (1986) predicted that through dissipation "*some materials vital for the current hot technology will sooner rather than later become extremely scarce (in the available form), even scarcer than the available energy from fossil fuels*". As examples, vanadium, tungsten, columbium (today niobium), cobalt and tantalum are named. This is remarkable considering that these metals are also considered critical in various studies that appeared in the recent years over twenty years after this announcement has been made. The scale of dissipative losses for critical metals is looked at in more details in section 3.1.

From a resource conservation or sustainability point of view, the reduction of dissipative losses – especially of materials that are already critical in terms of their economic importance and supply situation – appears to be a self-evident necessity. However, the actual development seems to go into a different direction. Critical materials are used in different ways that increase their likelihood to dissipate eventually. Reasons for dissipation of critical materials are for example

[21] Unlike polymers, principally the properties of metals can be restored fully (Wernick and Themelis 1998).

- their low concentration and relatively small amount in products;
- the growing variety of materials in products;
- the increasing miniaturization of products;
- the use in explicitly dissipative applications; and
- the use of material combinations that cannot be recycled by existing processing routes.

Besides the implications of resource conservation, dissipative losses may lead to contaminations of other materials flows from which they might only be removable with major efforts (e.g. accumulation of Cu, Ni and Cr in structural steel) (Gleich 2006) or to problematic (eco-) toxicological effects in organisms and ecosystems (e.g., Blaser et al. 2008; Kaegi et al. 2013). Contaminations of the hydrosphere have been observed for metals considered as critical, too, for example for rare earth metals like lanthanum, gadolinium, and erbium in the River Rhine (Kulaksız and Bau 2011; Kulaksız and Bau 2013) or niobium in fresh water (Filella, Magnenat, and Bensimon 2014). Here, a close relation of MFA aiming at quantifying dissipative losses and conventional risk assessment schemes and exposure assessment in particular becomes evident. The release of a substance into the environment is the prerequisite for environmental exposure and thus dissipative losses can be regarded as one form of environmental release, potentially resulting in exposure (Wigger et al. 2015; Wigger, Zimmermann, and Pade 2015). Against this background, reducing or avoiding dissipative losses is about preservation of resources as well as precautionary environmental protection (e.g., Gleich 2006).

3.1 Estimating the Dimension of Dissipative Losses for Selected Critical Metals

As already pointed out, dissipative losses of critical metals occur on a rather high scale. A first estimation on the scale of dissipation of critical materials has been published by Zimmermann and Gößling-Reisemann (2013). In this publication, a rather rough first quantification of relative dissipative losses on material level of materials considered critical by the EU (European Commission 2010) is presented. This material selection includes the “common critical metals” (germanium, indium, REE, and PGM; see section 2.1) as well as beryllium, cobalt, gallium, magnesium, niobium, tantalum, tungsten, and certain non-metallic materials (graphite, fluorspar).

In the study, the relative dissipative loss, i.e., the share of material that dissipates along the life cycle (at some time in the future) in relation to the amount of refined material entering the manufacturing stage today and assuming no significant changes to the recycling situation, is quantified. This is done based on EOL recycling rates among other data compiled from various sources including scientific articles and books, conference proceedings, and grey literature. Aggregated EOL recycling rates on material level have been available from (Graedel et al. 2011b; Graedel et al. 2011a). Details on the data used for the different metals are given in the supplementary information to (Zimmermann and Gößling-Reisemann 2013).

It has to be noted that in (Zimmermann and Gößling-Reisemann 2013), data referring to the worldwide situation has been used and the stage of mining has been excluded, i.e., the estimated dissipa-

tion rates refer to the life cycle stages between fabrication (starting with the refined metals) and end-of-life. Also, the approximation for the dissipation rate is based on today's situation, and it is ignored that many products have a life cycle that extends one year –for energy technologies such as gearless wind energy converters and thin-film photovoltaic cells for example by more than a factor of 20. For these metals that are relatively "young", currently there is a rapid building of stocks in the technosphere. End-of-life treatment with probable recycling, which are major sources of dissipation today will –in a larger scale– occur with some time delay. So far, only little experience regarding their EOL treatment exists and a, compared to the current situation, improved EOL treatment of these metals is likely or at least possible. According to this, the presented relative dissipative losses are rather an estimation that indicates the share of material that will dissipate eventually, given the present situation.

The screening shows rather high dissipative losses for most metals as presented in Table 7. More details on the methodological approach and results including a (qualitative) classification of losses are given in (Zimmermann and Gößling-Reisemann 2013).

Table 7: Estimations for relative dissipative loss for selected critical metals

Material	Relative dissipative loss	Based on data from
Antimony	>75%	(USGS 2012; Scharp 2009; Behrendt and Erdmann 2010; Angerer et al. 2009)
Beryllium	>80%	(USGS 2012; Cunningham 2004; Parsonage 2000)
Cobalt	>40%	(USGS 2012; Schüler 2011; Behrendt and Erdmann 2010; Buchert, Schüler, and Bleher 2009; Angerer et al. 2009; Hagelüken and Meskers 2009; Johnson et al. 2007)
Gallium	>95%	(USGS 2012; Kammer 2011; Buchert, Schüler, and Bleher 2009; Angerer et al. 2009; Behrendt and Erdmann 2010; Hagelüken and Meskers 2009; Classen et al. 2009; Handke 2008)
Germanium	>90%	(USGS 2012; Kammer 2011; Angerer et al. 2009; Hagelüken and Meskers 2009; Johnson et al. 2007; Buchert, Schüler, and Bleher 2009)
Indium	>90%	(USGS 2012; Kammer 2011; Buchert, Schüler, and Bleher 2009; Hagelüken and Meskers 2009; Angerer et al. 2009; Handke 2008)
Magnesium[22]	-	(USGS 2012; Papp et al. 2004)
Niobium	>50%	(USGS 2012; Angerer et al. 2009; H.C. Starck 2001)
Platinum Group Metals	Pt: 30-45% Pd: 40-50% Ru: ~85%	(USGS 2012; Loferski 2011; Behrendt and Erdmann 2010; Classen et al. 2009; Angerer et al. 2009; Buchert, Schüler, and Bleher 2009; Hagelüken and Meskers 2009; Handke 2008; Johnson et al. 2007; Sullivan 2006; Hagelüken, Buchert, and Stahl 2005)
Rare earths	>95%	(USGS 2012; Schüler et al. 2011; Schüler 2011; Buchert, Schüler, and Bleher 2009; Angerer et al. 2009)
Tantalum	>75%	(USGS 2012; Buchert, Schüler, and Bleher 2009)
Tungsten	>60%	(USGS 2012; Johnson et al. 2007)

According to the screening, most critical metals show rather high dissipative losses. Given the criticality of these metals, such high losses of these metals should be of serious concern. A look at the evaluation of criticality assessments presented in section 2.1 makes this problem even clearer. Among the metals that have been labeled critical in more than six studies, only the PGM show relative dissipative losses of below 90 %. Germanium, indium, gallium and the rare earths have dissipative losses of above 90 % as summarized in Figure 4.

[22] For magnesium, data availability did not allow to make an estimation of the relative dissipative loss.

Figure 4: Relative dissipative loss of common critical metals

3.2 Quantification of Dissipative Losses in Other MFA Studies

As pointed out in section 2.2 as well as in 3.1, literature on dissipative losses of critical metals is very limited. Still, there are some MFA studies quantifying dissipative losses, however, almost exclusively on material level without looking at single products in detail[23]. Such studies can be found especially for "traditional" metals like copper, lead or nickel (see section 3.2.1) but also for some precious (section 3.2.2) and critical metals (3.2.3). These studies differ significantly in their nomenclature when it comes to dissipation as well as in the material flows considered as (dissipative) losses. Losses and receiving media mentioned in the various studies include tailings, slags, sewage, in use dissipation, and dissipated landfill waste among others. Subsequently to the sections on MFA studies quantifying dissipative losses for various metals, the issue of nomenclature is looked into in more detail in section 3.3 including a more comprehensive list of terms used for losses in Table 8. Concluding, a definition and classification scheme for dissipative losses is presented in section 3.4.

3.2.1 Selected Uncritical Metals: Copper, Iron, Nickel, Aluminum and Lead

Copper

Copper use and related losses are relatively well studied. Regional copper flow analyses have for example been published by Bader et al. (2011) for Switzerland, by Zeltner et al. (1999) for the U.S., and by Spatari et al. (2002) for Europe. Rather detailed analyses with regard to losses have been performed by Lifset (Lifset et al. 2002; Lifset et al. 2012). In (Lifset et al. 2002) a quantitative assessment of copper stocks and flows throughout the technosphere is presented. Losses to the environment (leakage) are highlighted regarding their possible toxic behavior. Furthermore copper losses in different life cycle stages are quantified –copper in tailings, in smelting slags and copper disposed on landfills. Also dissipative losses arising in the product use phase are mentioned as a release often neglected in environmental sciences. Use in pesticides, paints, adhesives, solvents and tires are given as examples (Lifset et al. 2002). It is stated that from the entire amount of copper produced in the 20th century about 85 % remains still in use (as of 2002). Smelting and milling are identified as the most significant stages in terms of material losses (Lifset et al. 2002). In the U.S., about 14 % of the metal

[23] The study by (Nakajima et al. 2007) analyzing the use of indium in flat panel displays in Japan is one exception but only provides a rather rough estimation of dissipative losses without differentiation of the receiving media.

content of the ore is lost to tailings and slag. Dissipative losses, however, are not further quantified in this study, an aspect which is addressed in (Lifset et al. 2012). Here, a historical analysis of copper dissipative releases in the U.S. from 1975 to 2000 is performed. Intentional releases (fungicides, animal feed, fireworks, etc.) are quantified to 13,800 Mg in 1975 to 11,900 Mg in 2000. Unintentional releases from intended uses (e.g., brake pads, corrosion, vehicle leaks) amount to about 7,600 Mg in 1975 and 13,300 Mg in 2000. Trace contaminant releases for example from coal, oil, or wood combustion are quantified to about 1,300 Mg in 1975 and 1,900 Mg in 2000 (Lifset et al. 2012). The authors conclude that dissipative releases of copper do not occur in an order of magnitude that represents a significant loss in resource terms (Lifset et al. 2012).

Lead

Losses of lead from its anthropogenic cycle are analyzed in detail by Mao, Cao, and Graedel (2009). In this study, the anthropogenic lead cycle for the year 2000 in 52 countries is investigated. Seven material flows leading to losses are considered: tailings, slag, fabrication and manufacturing, dissipation from use, hibernation, landfilling, and dispersion following product discard (Mao, Cao, and Graedel 2009). On a global level, lead losses are quantified to about 3,000 Gg in 2000. This is compared to the global flow of about 6,300 Gg in 2000 meaning that for every kg entering use in 2000 about 0.48 kg are lost to the environment (Mao, Cao, and Graedel 2009). The total losses are broken down to seven different loss types: 16.4 % tailings, 7.1 % slag, 2.2 % fabrication and manufacturing, 20.7 % dissipation from use, 14.8 % dispersed after discard and 34.4 % landfilled. Regarding the use phase, the losses are further divided into air emissions (5 %), emissions to water (5 %) and emissions to land (90 %) (Mao, Cao, and Graedel 2009).

Nickel

Reck et al. (2008) analyze the anthropogenic nickel cycle for the year 2000. They conclude that from nickel losses 36 % go to landfills, 33 % to tailings, 15 % into slag and 12 % leaving to other metal's scrap markets (i.e. other material flows). In (Eckelman, Reck, and Graedel 2012) the global flows of nickel are assessed using markov chain models. Here, the authors conclude that over time nickel (after approximately three to four life cycles) is lost to the environment and as a tramp element to carbon steel (Eckelman, Reck, and Graedel 2012).

Iron

The anthropogenic iron cycle is analyzed in (Wang, Müller, and Graedel 2007) for the year 2000. Iron losses are quantified for Asia (64 Tg/a), North America (47 Tg/a) and the Commonwealth of Independent States (32 Tg/a). It is stated that iron releases into the environment and other repositories consist of 43 % tailings, 40 % landfill and dispersion, 13 % slag and other byproducts, and 4 % in-use dissipation (described to be mainly corrosion) (Wang, Müller, and Graedel 2007). Also, loss ratios

(sum of losses[24] divided by flow to use phase) are given for different continents with 0.33 for Africa, 0.21 for Asia, 0.83 for CIS, 0.20 for Europe and 0.29 for North America.

Aluminum

An estimation of aluminum losses (1.2 Mio. metric tons in 2002) –without more detailed analyses– can be found in (European Aluminium Association 2004).

3.2.2 Precious Metals

PGM

Saurat and Bringezu (2008; 2009) analyze the PGM flows (covering platinum, palladium and rhodium) in Europe in 2004. Major losses are reported in a non-dissipative way, i.e. in terms of exports of PGM containing products like cars. Other (dissipative) losses are stated to occur in processes subsequent to mining. They are quantified to 15 % in milling-concentrating and 4% for pyrometallurgy in relation to the input flows (Saurat and Bringezu 2008). It is furthermore mentioned that a recycling infrastructure exists but losses might still occur along the multistage recycling process. A much more detailed analysis of PGM flows is performed for Germany by Hagelüken, Buchert, and Stahl (2005). Here, for different PGM applications losses along the life cycle and in recycling processes are quantified. This analysis shows a relatively efficient recycling infrastructure for most catalyst types (with catalysts being the major field of applications of PGM). The problem of exports especially of used cars is highlighted here as well. For the different catalyst types, losses in the use phase are quantified, too. Significant higher losses are reported for PGM in electronics (>60 %), and other industries (glass, galvanic industry, dental industry) (Hagelüken, Buchert, and Stahl 2005).

Silver

Besides the PGM, silver appears to be relatively well studied among the precious metals. A detailed analysis of global silver emissions to land, water and air has been conducted by Eckelman and Graedel (2007). This includes a quantification of different types of losses (landfill, particulates, direct to water, direct to land, leachate, tailings, slag) for different regions of the world. These emissions or losses are partly referred to as dissipation. This is looked at in more detail in section 3.3. Furthermore, relative losses for each life cycle stages are identified. In the material production stage about 20 % of the silver contained in the extracted ores is lost as tailings (Eckelman and Graedel 2007). For fabrication and manufacturing 0.2 % losses are mentioned, while no quantification is presented for the use phase (Eckelman and Graedel 2007). Lanzano et al. (2006) furthermore analyze the stocks and flows of silver in Europe in the year 1997. This also includes a quantification of losses to the environment which amounts to 1,740 Mg per in 1997.

[24] This includes slags, tailings, other by-products, landfill, dispersion to environment, and in-use dissipation.

3.2.3 CRITICAL METALS

As mentioned above, the REE and PGM appear to be the most studied metals among the "common critical metals" while only few publications can be found on gallium, germanium, indium, and tellurium.

Rare earth elements

Du and Graedel (2011c) analyze the global cycles of rare earths in 2007 on a rather aggregated level; here, gaps as well as discrepancies in the underlying data are mentioned. Still, relative losses along the life cycle are quantified. For lanthanum it is stated that 20 % of the metals mined in 2007 was lost to tailings at the mining stage. Another 10 % are lost during separation as slag, another 10 % during the fabrication of intermediated products, and 5 % during the manufacturing of the final product (Du and Graedel 2011c). At EOL due to lack of post-consumer recycling a complete loss is described (Du and Graedel 2011c). A loss of 20 % to tailings, 10 % to slag, and 10 % in the fabrication of intermediate products can be considered as typical for rare earth metals (Du and Graedel 2011c). Slightly different losses for rare earths are mentioned in (Du and Graedel 2011a) with 25 % losses to tailings, 5 % to slag, and 10 % losses in product manufacturing. However, it is mentioned that these are estimations based on "typical efficiencies" of modern industrial fabrication without underlying data specific for rare earths (Du and Graedel 2011a). The difficulty of acquiring a comprehensive picture of use and loss of rare earths due to data availability is also mentioned (Du and Graedel 2011b).

Gallium, germanium, indium, and tellurium

According to Chen's and Graedel's review on anthropogenic cycles of elements (Chen and Graedel 2012) only few studies on gallium, germanium, and tellurium are available, mainly focusing on Japan. Studies reporting dissipative losses of these metals have –to the author's knowledge– not yet been published. For indium slightly more studies can be found. Wittmer et al. (2011) intended to quantify (dissipative) losses for gallium and indium, but due to data availability no quantification of losses for gallium and only a very rough estimation for indium losses from primary production (500-700 Mg/a) is performed. By Yoshimura, Daigo, and Matsuno (2011) the global indium losses in 2004 from mining and smelting are quantified to 8-11 % or 4,826 Mg, respectively, and the losses from manufacturing are quantified to 310 Mg[25]. A detailed substance flow analysis of indium for flat panel displays in Japan has been published by Nakajima et al. (2007). Here, dissipative losses of indium used in flat panel displays in 2004 in Japan are quantified to 220 Mg. Overall, a great demand for further research regarding material flows of critical metals in general and especially with a focus on dissipative losses can be identified.

3.3 NOMENCLATURE

There are various studies dealing explicitly or implicitly with dissipative losses (see section 3.2) but a great diversity regarding the understanding of dissipation can be observed. In some studies, some

[25] Study in Japanese, only abstract available in English.

losses are explicitly referred to as dissipation while other losses are referred to as slag, tailings, etc. Anticipating the definition of dissipative losses given in the following section, it needs to be said that in this thesis, it is assumed that there are basically no "non-dissipative" losses. "Dissipative" does not only refer to a material's concentration but also to the feasibility of recovery. Exports out of the system boundaries as considered for example by Hagelüken, Buchert, and Stahl (2005) or hibernation of products as considered by Mao, Cao, and Graedel (2009) are not regarded as losses in this study. Further details on this are given in section 3.4 and the description of the methodology in chapter 4.

As said, among the various studies described in section 3.2, nomenclature and understanding of dissipative losses are diverse. Elshkaki et al. (2009), for example, focus on unintentional material losses without regarding their dissipative nature while Eckelman and Graedel (2007) differentiate between the quality of the emissions (their chemical form, emission route) and their receiving media and refer to some of these losses explicitly as "dissipation" while others are named after their chemical form (e.g. particulate) or their emission route (e.g. recycling losses, ash to landfill) (Eckelman and Graedel 2007). An explicit definition of what is understood as dissipation is not given. No differentiation of receiving media is, for example, made by Lanzano et al. (2006) in their analysis of silver losses to the environment in Europe in 1997 and, again, dissipation is only used to describe some releases ("dissipated landfilled waste") while other losses (tailings, slag, sewage, ashes) are not referred to as dissipative losses.

In the rather detailed analysis of lead losses to the environment by Mao, Cao, and Graedel (2009), dissipation is, again, mentioned as a specific type of loss (dissipation in use phase) besides other losses, i.e. tailings, slag, fabrication and manufacturing, hibernation, landfilling, and dispersion following product discard (Mao, Cao, and Graedel 2009). Regarding losses from the use phase, the following examples are named explicitly: corrosion of lead pipes and roofing lead, dissipation of lead in ammunition, lost lead fishing weights, and combustion of lead-containing motor fuels. As receiving media, air, soil, water bodies, and sediments are mentioned (Mao, Cao, and Graedel 2009). For losses from the end-of-life stage (waste management and recycling), landfilling is mentioned for lead e.g. in incinerator ash, cathode ray tubes, consumer electronics. Also losses at EOL in form of dispersion, e.g. from losses during transport, incineration without landfilling and incinerator ash used in pavement are mentioned but not described as dissipative (Mao, Cao, and Graedel 2009).

The use of term dissipation exclusively for losses from use can also be found in other studies (e.g., Rauch and Pacyna 2009). Still, there are also studies using "dissipation" exclusively for losses at end-of-life (e.g., Nakajima et al. 2007).

A summary of the terms used explicitly and implicitly for dissipative losses in the different studies is shown in Table 8. Due to the inconsistencies in the terminology between the studies the table includes waste streams (e.g., slag) as well as chemical forms (e.g., particulate) and applications leading to dissipative losses (e.g., pesticides). It becomes clear that there is no general consistent understanding on what losses should be referred to as dissipative. And neither is there a consensus on the

receiving media that should be considered. Again, it needs to be highlighted that hibernation actually is not a dissipative loss. Over time, however, dissipative losses to the environment might occur.

Table 8: Terms for dissipative releases in the literature (compiled from the studies described in section 3.2)

Life cycle stage	**Production**	**Manufacturing and fabrication**	**Use phase**	**End-of-life**
Waste streams or applications leading to dissipative releases	Leachate dust smelting slag tailings sewage bottom and fly ash waste water	F&M losses recycling losses	Pesticides paints and coatings animal feeds fertilizers fireworks tear and wear corrosion leaks fuel additives untreated sewage hibernation ammunition fishing weights	Waste management ash to landfill particulate landfilled waste incineration (ash)
Receiving medium	Environment: soil, water, air			

Still, there are two studies with a relatively consistent understanding of dissipative losses that need to be highlighted. These studies, conducted by Lifset et al. (2002; 2012), deal explicitly and in detail with dissipative losses of copper including a definition of dissipation. Here, dissipative losses are understood as the "*final releases of material to the environment*" (Lifset et al. 2002). Some examples given for dissipative flows are leachate, dust, particulates, or ash. This is a major difference to some of the studies considered in section 3.2 that –as described above– considered only, e.g., "slags", or "losses in manufacturing" as destination of the dissipating material.

Furthermore, Lifset et al. (2002; 2012) make a distinction between dissipative release and dissipative use. It is said that dissipative releases are *"releases from products that are not easily recovered or recycled"* while dissipative uses can be considered as *"uses of a substance where the dissipative release is intentional*" (Lifset et al. 2012). Addressing this, a framework for classification of dissipative losses is presented, considering the intentionality of use and release. The following categories and losses are considered (Lifset et al. 2012):

- Intentional releases from intentional use: Land-applied pesticides, water-applied pesticides, copper in marine paints, animal feeds, fertilizers, and fireworks.
- Unintentional releases from intentional use: Brake pad wear, copper pipe corrosion, architectural uses, copper in treated wood, vehicle fluid leaks, industrial effluents, mining and production of copper, and municipal solid waste management.
- Trace contaminant releases: Copper in fossil fuels, mining and production of other metals, tire wear, and wood combustion.

Even though the considered studies differ in the used terminology, and only Lifset et al. (2002; 2012) provide a somewhat consistent framework, there seems to be an agreement regarding the environment (sometimes with differentiation of the compartments air, soil and water) as single (or final) receiving medium for dissipative material releases, which is not entirely adequate as described in the following section. Also, there is still a need for consensus regarding understanding and methodological implication of dissipative losses in MFA studies, which will be addressed in the following as well.

3.4 Definition and Classification Scheme for Dissipative Losses

Against the background of the described inconsistency in nomenclature, a definition of dissipative flows and losses and a framework for their classification is presented in this section[26]. The dissipative releases considered in other studies (Table 8), the definition provided by Lifset et al. (2012) (*"releases […] that are not easily recovered or recycled"*) as well as the fact mentioned at the beginning of chapter 3 that matter exists between two extremes –available and unavailable (Georgescu-Roegen 1986)– immediately suggest using the change in a material's availability for any definition of dissipative losses of material. Also, the material's availability is of fundamental importance regarding any conclusion aiming at the sustainable management of metals and resource conservation. It has to be noted, though, that the term "availability" is not used in the strict understanding from thermodynamics (as described, for example, in Keenan 1951; Kestin 1980), but in a more practical way describing the material's feasibility of recovery. While the existence of a state of absolute unavailability of matter is argued (e.g., Georgescu-Roegen 1986), the economic (or technological) feasibility of recovering a material appears to be a good criterion to assess dissipation. While the majority of the studies considered in the previous sections (see sections 3.2 and 3.3) considers the environment as the only receiving medium for dissipative losses, in the definition and classification scheme presented below the additional consideration of dissipation to landfills and other material flows is suggested which is motivated in the following.

Landfills are also considered within some of the studies regarded in section 3.2, but only as an intermediate storage with further dissipation into the environment. Depending on the quality of the landfill, further dissipation into the environment is, of course, possible, but usually only on a relatively small scale, and the majority of the material will remain in the landfill at least within time frames relevant in the context of this thesis (e.g., within time frames relevant for optimizations of metals management or urban mining activities). Therefore, landfills are considered a relevant receiving medium for dissipative losses.

Losses to other material flows occur especially during material recycling, i.e. at the fabrication and manufacturing stage (recycling of production scrap) as well as at product end-of-life; for some products a complete dissipation into other material flows during the use phase can be observed as well. In

[26] The definition of dissipative losses and the classification scheme have previously been published in (Zimmermann and Gößling-Reisemann 2013), and parts have been republished with some minor refinements in (Zimmermann and Gößling-Reisemann 2015).

the recycling of multi-material products, a complete separation of the different materials is hardly possible, and depending on the applied processes and the target materials, other materials will end up in dust and slag etc. and to some extent as a contaminant in the target material (Zimmermann and Gößling-Reisemann 2015; Reuter et al. 2013; Castro et al. 2005; Castro et al. 2004). These contaminants may have a significant impact on the material properties in some cases (e.g., dissipation of copper into steel); while in other cases the wanted material properties may remain unaltered. Either way, as a contaminant in other material (i.e., as an unwanted part of other products) the dissipated material is further used in goods and products and remains in the technosphere (Zimmermann and Gößling-Reisemann 2015). Other material flows might, for example, also include slags that are used as construction material in, e.g., road construction. From these other material flows further dissipation to landfills or into the environment might occur depending on the respective products and their use. Analyzing the further fate of the respective material will, however, often be out of the scope of many studies or impeded by data availability. Especially for "other material flow products" with high turnover rates (relatively short lifespans), considering the further fate of dissipative losses into other material flows might provide valuable additional information.

Against this background, the following definition of dissipative losses is suggested and used in this thesis (Zimmermann and Gößling-Reisemann 2013):

> "*Dissipative losses are losses of material into the environment, other material flows, or permanent waste storage that result in concentrations in the receiving medium, such that a recovery of these materials is technically or economically unfeasible.*"

In this definition, the change in a material's availability is addressed by the technical or economic feasibility of recovering the material. This includes a dynamic element; the technical and economic feasibility depend on the current technical knowledge and the market situation for the respective metal. This means, losses that must be considered dissipative today might be less dissipative in the future because of new technologies, changing economic incentives, etc., although the physical dissipation (i.e., the change in the material's concentration and the thermodynamic availability) might be the same. Furthermore, this implies that there are no non-dissipative losses. Material is either recovered or lost to one of the three media making its recovery (currently) unfeasible. In this regard, exports (of waste products or products in use) to other countries which are considered as losses in some studies (e.g., Hagelüken, Buchert, and Stahl 2005) due to the definition of system boundaries, are not to be considered instantaneously as dissipative (or non-dissipative) losses. Such exports will, however, lead to dissipation and recycling, eventually, depending on the further use and disposal of the products. Aspects like hoarding of products are neither dissipative losses in that sense as they are merely an extension of the domestic service lifespan of a product (i.e., by a "dead storage span", cf. section 4.4), with possible consequences regarding the potential occurrence of dissipative losses, though.

Besides the economic situation (market situation) and the technical knowledge, the feasibility of recovery also depends on the medium the material is released into. Based on the receiving media a qualitative assessment of the severity of dissipative losses can be performed. Severity in this context is considered as the unfeasibility of recovering the material. Against this background, dissipation into the environment has to be considered the most severe or "the most dissipative one". The dissipated material (originating from, e.g., pesticides, wear and tear, or corrosion) will usually be dispersed over a wide area. Transfer from one compartment (air, water, soil) to another is possible and once the material has been emitted to the environment it might tend to chemically and physically transform. A targeted recovery is nearly impossible under such circumstances. For dissipation into other material flows it can be said that there is at least a theoretic possibility of recovering the material. Depending on the lifespan of the product bearing the dissipated material as a contaminant, sooner or later the product will reach its end-of-life and will be potentially recycled. A targeted recycling of the dissipated material is, however, very unlikely.

For dissipation to landfills, there is no or at least only a very limited "mobility" of the dissipated material; the locations of landfills are usually well known. Further dissipation into the environment might be possible, but, as said above, usually not on a significant scale. Even though the concentration of metals in landfills might be difficult to measure, material flow analyses can help in this endeavor. However, landfills usually contain a variety of different materials in hardly known concentrations, and a recovery might often only be feasible for high volume metals like steel, copper or aluminum (Zimmermann and Gößling-Reisemann 2013; Zimmermann and Gößling-Reisemann 2015). A general differentiation of the severity of dissipation into other material flows and landfills is not possible, though. Dissipation into other material flows also includes dissipation into, e.g., incineration residues or recycled metal that might be used for construction purposes with no higher mobility than landfills and equal turnover rates.

Besides the receiving media, dissipative losses can be further classified based on the location of occurrence, which is in accordance with most MFA studies considering losses. This differentiation is especially important for identifying potential optimizations and improvements towards a more sustainable materials management. An illustration of the classification based on receiving media and life cycle stage of occurrence is given in Figure 5.

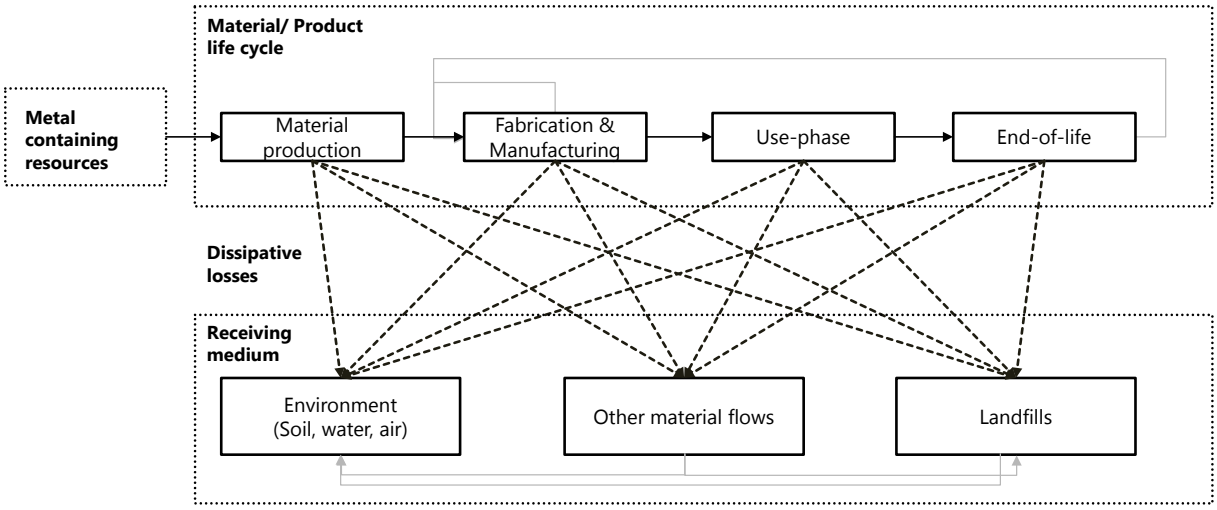


Figure 5: Classification scheme for dissipative losses[27]

As shown in the figure, dissipative losses can principally occur at every step of a material's life cycle; starting with the extraction of raw material and metallurgical refining (summarized under material production), fabrication of semi-products, manufacturing of products as well as treatment of production waste and scrap (summarized under fabrication and manufacturing), use phase and end-of-life including collection and dismantling of products as well as waste treatment including recycling and incineration. Table 9 gives some examples for losses along the life cycle into the different media.

Table 9: Examples for dissipative losses ordered according classification scheme

	Receiving media		
Life cycle stage	**Environment**	**Other material flows**	**Landfills**
Material production	Leaching/leachate from mine tailings; dust	Contamination within co-production of metals.	Landfilling of mine tailings.
Fabrication & Manufacturing	Dissipation through material/particulates contained in steam/ off-gas.	Dissipation in recycling of manufacturing scrap: Contaminants in recycled material.	Landfilling of production scrap.
Use Phase	Wear and tear (e.g., of coatings, brake pads), fuel additives, pesticides, corrosion.	Dissipation of catalysts (e.g., Ge, Ti, Sb) into the final product (e.g., PET).	(-)[28]
End-of-Life	Releases from insufficiently sealed landfills.	Dissipation in recycling processes: Contaminants in recycled material.	Landfilling of metal containing slags.

[27] Adapted versions have been published in (Zimmermann and Gößling-Reisemann 2015; Zimmermann and Gößling-Reisemann 2013).

[28] Dissipation from use phase to landfills is not envisaged in the MFA methodology, as disposal and potential landfilling are allocated to the end-of-life phase. Still, some examples could be constructed: E.g., the use phase of a garbage sack might comprise its disposal on landfills; the use phase of certain construction materials might comprise their use on landfills.

4 MFA METHODOLOGY AND REFINEMENT

The method of material flow analysis is the core tool within this thesis and in the analysis of the case studies, respectively. The focus of this thesis is on analyzing dissipative losses along the life cycle of selected products, i.e., a product-centric approach is chosen, and in addition, present and future absolute material flows including material demands, secondary material flows as well as dissipative losses are analyzed. To the author's knowledge, comparable studies (detailed prospective product-centric analysis of dissipative losses along the life cycle of products) have so far not been carried out and accordingly, some methodological refinement is required.

Against this background, in section 4.1 an introduction into MFA methodology and its role in industrial ecology is given. In section 4.2 a brief generic description of the product life cycle as the central object of study is presented. Different types of MFA studies are described in section 4.3 while the role of lifespans and how to deal with them in dynamic MFA studies is examined in section 4.4. A synopsis of these descriptions focusing on product-centric MFA is given in section 4.5, before the consideration of dissipative losses according to the classification scheme presented in chapter 3.4 is described in section 4.6. Concluding the chapter, a general description on the data requirements in the case study analysis and on how uncertainties etc. are dealt with in the analysis of the case studies is given in section 4.7.

4.1 MFA AND INDUSTRIAL ECOLOGY

Material flow analysis, i.e., the study of anthropogenic material flows or cycles within socio-economic systems, is a central tool within industrial ecology. The field of industrial ecology is built around the fact that many biological ecosystems are particularly effective at recycling resources and are therefore considered as useful examples how industrial systems should be designed. This is often referred to as the "biological analogy" (Lifset and Graedel 2002). In addition, industry as "human technological activity" (Lifset and Graedel 2002) is placed in the context of the ecosystems supporting it, examining the sources of resources used in society as well as the sinks that may absorb or detoxify industrial waste and emissions. Hereby industrial ecology is linked to questions of carrying capacity and ecological resilience. This means, in industrial ecology a system perspective is taken and socio-economic systems are viewed in context with their surroundings (Lifset and Graedel 2002). These elements are summarized by White (1994) by defining industrial ecology as "*the study of the flows of material and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influence of economic, political, regulatory, and social factors on the flow, use, and transfor-*

mation of resources" emphasizing the importance of the MFA methodology[29] within industrial ecology.

MFA aims at understanding the "industrial metabolism" of the analyzed system in terms of the exchange of matter and energy between system components and with the environment (cf. Zimmermann and Gößling-Reisemann 2015). The concept of a metabolism, as used in the science of ecosystems, is hereby applied to industrial systems (Fischer-Kowalski 2002). While in the beginning the science of studying the industrial metabolism was rather narrowly focused on analyzing energy and material exchange between societies and the environment from a macro perspective (Fischer-Kowalski 2002), today MFA is also widely applied to analyze historic and prospective material flows linked to the use of specific products and technologies, and to analyze flows of materials on the corporate level (cf. Zimmermann and Gößling-Reisemann 2015), providing valuable knowledge for companies as well as policymakers required to achieve sustainable resource management (Chertow et al. 2014).

In addition to the analytic purpose of MFA in terms of gaining knowledge about the industrial metabolism, there is a hidden agenda of MFA as described by Brunner and Rechberger (2004) with resource conservation and environmental protection as its central objectives. This is well in accordance with the goals of industrial ecology as well as with the objectives of sustainable metals management as described in section 2.3, such as creating closed-loop industrial practices, controlling pathways for material use in industrial processes, and balancing industrial input and output with the carrying capacity of ecosystems in order to maintain or improve environmental quality (Brunner and Rechberger 2004; Lifset and Graedel 2002). The hidden agenda of MFA is well reflected in the goals of most MFA studies (cf. Zimmermann and Gößling-Reisemann 2015) as well as in reviews on MFA studies by Chen and Graedel (2012) and Müller et al. (2014).

The MFA methodology is built around a systems approach and the principle of mass balance. It analyzes the throughput of materials along process chains that usually comprise the life cycle of products or materials, including stages such as material production, fabrication and manufacturing, use phase, and end-of-life. The principle of mass balance implies that all inputs to a system are either accumulated within the system or appear as outputs at the system boundaries. Depending on the respective goal and scope of the study, some stages might be divided into various single process steps and be analyzed in detail while other stages might be regarded as black boxes or omitted. The system boundaries define what processes are to be included in the study, spatially as well as temporally.

In MFA, the term material can comprise single substances (chemical elements or compounds; e.g., iron, steel, copper, nitrogen, cellulose) as well as goods (e.g., steel billets, copper pipes, flat screen televisions, automobiles). Material flows are defined by mass (of material) per time, e.g. by units

[29] The general description of MFA methodology as well as the description of the methodological refinement and specifics for the analysis of the case studies (dynamic product-centric MFA) have partly been previously published in (Zimmermann and Gößling-Reisemann 2015).

such as grams, kilograms, or Megagrams (metric tons) per day, month, or year. As long as the context is clear, even energy flows (measured in, e.g., Joule or kilowatt-hours per year) can be interpreted as "material" (cf. Zimmermann and Gößling-Reisemann 2015). In contrast to this, studies focusing on single substance are sometimes referred to as substance flow analysis (SFA) (e.g., van der Voet 2002). Often, however, both terms are used synonymously. Studies of a single substance are also sometimes referred to as MFA (Brunner and Rechberger 2004), as it will be done in the following, too.

A generic industrial system consisting of several processes (process A-E) and their connecting material flows (x_i) is shown in Figure 6. The principle of mass balance can be applied to this generic system on a system level (i.e. –in a simple case assuming there is no accumulation of stocks within the system– as $x_1 + x_2 + x_3 = x_8 + x_9$; or with accumulation of stocks as $x_1 + x_2 + x_3 = x_8 + x_9 + \Delta Stock_{A-E}$ with $\Delta Stock_{A-E}$ representing the change of stocks in the system) as well as on process level (i.e. for process A as $x_1 = x_4$, or $x_1 = x_4 + \Delta Stock_A$, respectively).

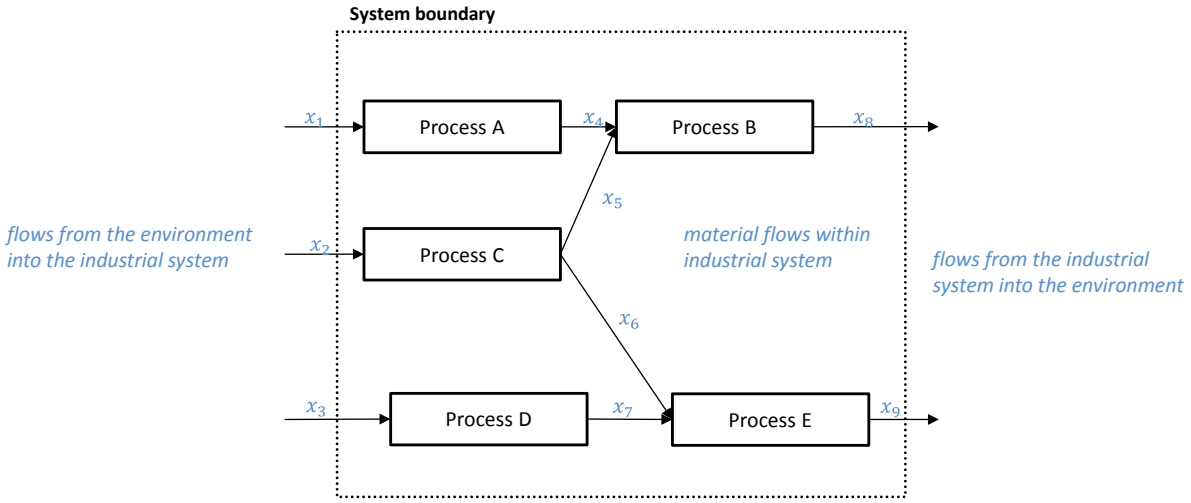


Figure 6: Material flows in a generic industrial system

The spatial definition of the system boundaries often covers a certain geographic area such as a single country, a continent, or the entire globe. It is, however, also possible to use the life cycle of materials or products to define the spatial boundaries. While use phase and probably end-of-life might take place in one country, material production as well as fabrication and manufacturing might take place in different countries, i.e. the relevant material flows and the system boundaries, respectively, might stretch over various countries.

Temporally, it needs to be defined whether the study looks at a snapshot in time like a reference year (i.e., whether it is static) or whether it looks at multiple periods of time (i.e., whether it is dynamic). Also, retrospective studies investigating material flows of past periods and prospective studies investigating potential future material flows need to be distinguished. Further details on methodological differences between MFA studies are given in section 4.3.

4.2 Life Cycle of Products

In many MFA studies, material flows are analyzed along the life cycle of a product or a material. The product life cycle comprises upstream and downstream processes linked to the use of the analyzed product, while the life cycle of materials may comprise the use of material in various products. In both cases, analysis and underlying model are commonly structured into four phases (as also noted by Chen and Graedel 2012 in their review of MFA studies), material production, fabrication and manufacturing, use phase, and end-of-life. This generic life cycle of a product is shown in Figure 7.

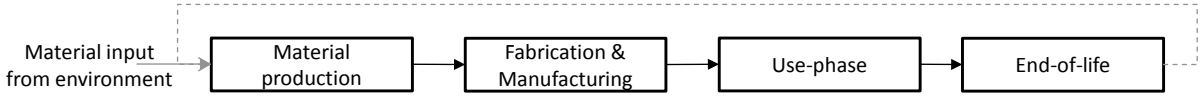


Figure 7: Generic life cycle of a product

Material production (MP) comprises all steps from the extraction of the material from its extraction reservoir to its transformation to elemental or related forms (e.g., desired oxides or alloys). These steps are, of course, material specific, but often in MFA mining (including milling) and smelting, and sometimes refining are mentioned explicitly as major steps within the material production phase. Accordingly, quite generally, the production of primary metals can be broken down into the following steps (cf. Graedel, Gunn, and Tercero Espinoza 2014):

- Mining the ore;
- Beneficiation: separating the metal-containing raw materials from waste material;
- Smelting: transforming the metallic compounds (e.g., oxides and sulfides) into impure metal;
- Refining: purifying the smelted metal.

Fabrication and manufacturing (F&M) is the next main life cycle stage and comprises all steps following the MP stage until the completion of the final product. Mostly, the process phases of F&M are looked at together (as for example done in Graedel et al. 2004; Spatari et al. 2002; Graedel et al. 2002 and described in the review by Chen and Graedel 2012). Although no universal differentiation of both stages exists, in MFA context fabrication commonly describes the first processing steps of the analyzed material which results in an intermediate product. For example, the use of a refined material for casting, alloying, plating, but also (semi-) products like catalysts or batteries, wire, rods, sheet, bars or ingots can be found to be accounted to the stage of fabrication in MFA studies. Manufacturing, on the other hand, comprises all subsequent steps that finally result in the final product which then enters the use phase.

The use phase comprises the product specific use until it reaches the end-of-life phase. It may also include the use by a potential second or third owner of the product as well as “dead-storage time” during which the product is not actually used. The use phase ends with the discard of the product by its final owner. Further differentiations of the use phase are discussed in section 4.4.

The end-of-life (EOL) phase comprises various different EOL options such as re-manufacturing and recycling, incineration and landfilling.

4.3 Types of MFA Studies

Various types of MFA studies can be distinguished based on the definition of system boundaries, the consideration of temporal dynamics, material aggregation, model structure, and other methodological elements. The issue of system boundary definition has already been briefly addressed in section 4.1. Spatially, the system boundaries may cover the entire globe (e.g., Eckelman, Reck, and Graedel 2012; Kavlak and Graedel 2013), a single country such as Germany (e.g., Zimmermann, Rehberger, and Gößling-Reisemann 2013; Hagelüken 2005), or any other geographic reference area. In this case, material flows located outside of the system boundaries are not included in the analysis. Alternatively the life cycle of specific products can be used to define the spatial boundaries (i.e., material flows related to the use of a specific product in a geographic reference area, e.g., CIGS photovoltaic cells used in Germany). In that case, material flows connected to MP, F&M, use by second and further owners, and EOL are included in the analyzed system regardless of their location. Temporally, prospective studies, which look at future developments, and retrospective studies, which analyze the past, as well as dynamic and static studies need to be distinguished. So far, static studies appear to be the vast majority compared to dynamic studies with roughly ten times as many studies published, as a review by Chen and Graedel (2012) shows.

Besides the fact that dynamic models analyze material flows over a period in time and provide knowledge about the development of resource use, they –unlike static models– allow for the consideration of stock development, i.e., accumulation of materials in the technosphere, by observing flows. In contrast, in static modeling, stocks can only be considered by direct observations (i.e., following a bottom-up modeling approach) or if the information has been previously available. In-use stock estimations particularly gained interest in the past years (Murakami et al. 2010). As dynamic models provide more information than static models they also require additional input, i.e., information regarding the time dimension and especially regarding the lifespan of the material or product under study (cf. van der Voet 2002). There are various different understandings of the term lifespan, a fact which is looked at in detail in section 4.4. Methodologically, lifespans can be considered in dynamic models in two different ways, either by leaching models (sometimes referred to as depreciation models) or by delay models (Murakami et al. 2010; van der Voet 2002). In leaching models the outflow (e.g., waste, EOL products) is determined as a fraction of the present stock; the respective coefficient in the model is called loss-, emission-, or leaching coefficient. Delay models on the other side start from the assumption that the outflow is not determined by the size of the stock but by past inputs into the system and residence times (van der Voet 2002). In delay models time series for input flows and lifespan distributions for output flows are used (Murakami et al. 2010; Elshkaki et al. 2005).

Among dynamic models, a methodological differentiation can be made between top-down and bottom-up approaches with regard to the estimation of the in-use stock. Bottom-up in-use stock estima-

tion is based on observations of the direct amount of stock and thus does not necessarily require any lifespan information (Murakami et al. 2010). Top-down in-use stock estimations on the other hand are determined based on the net-flows into use, i.e., as the balance of input and output flows (Murakami et al. 2010; Müller et al. 2014; cf. Zimmermann and Gößling-Reisemann 2015). This requires information of either inputs and outputs or inputs and lifespans.

The last methodological difference to be highlighted here is that one between material-centric and product-centric studies. Product-centric studies focus on material flows linked to specific products such as photovoltaic cells (e.g., Zimmermann 2013a), wind energy converters (e.g., Zimmermann, Rehberger, and Gößling-Reisemann 2013), flat panel displays (e.g., Nakajima et al. 2007) or a branch of products such as low-carbon technologies (e.g., Nansai et al. 2014) or electricity generation technologies (e.g., Elshkaki and Graedel 2013). Material-centric studies on the other hand look at flows of material across all fields of application, analyzing for example the global nickel flows (e.g., Eckelman, Reck, and Graedel 2012), the silver flows in Europe (e.g., Lanzano et al. 2006), or the flows of PGM in Germany (e.g., Hagelüken 2005).

4.4 Lifespans in Dynamic MFA Models: Definition, Data, and Distributions

The lifespan is an essential parameter in dynamic delay models. It determines how long products remain in the use phase and thus determines in-use stock and output flows over time. However, various differing definitions exist in science and literature as highlighted by Murakami et al. (2010), and hence the term “lifespan” needs to be clarified. An overview of different “spans” defining a product’s life cycle is given in Figure 8.

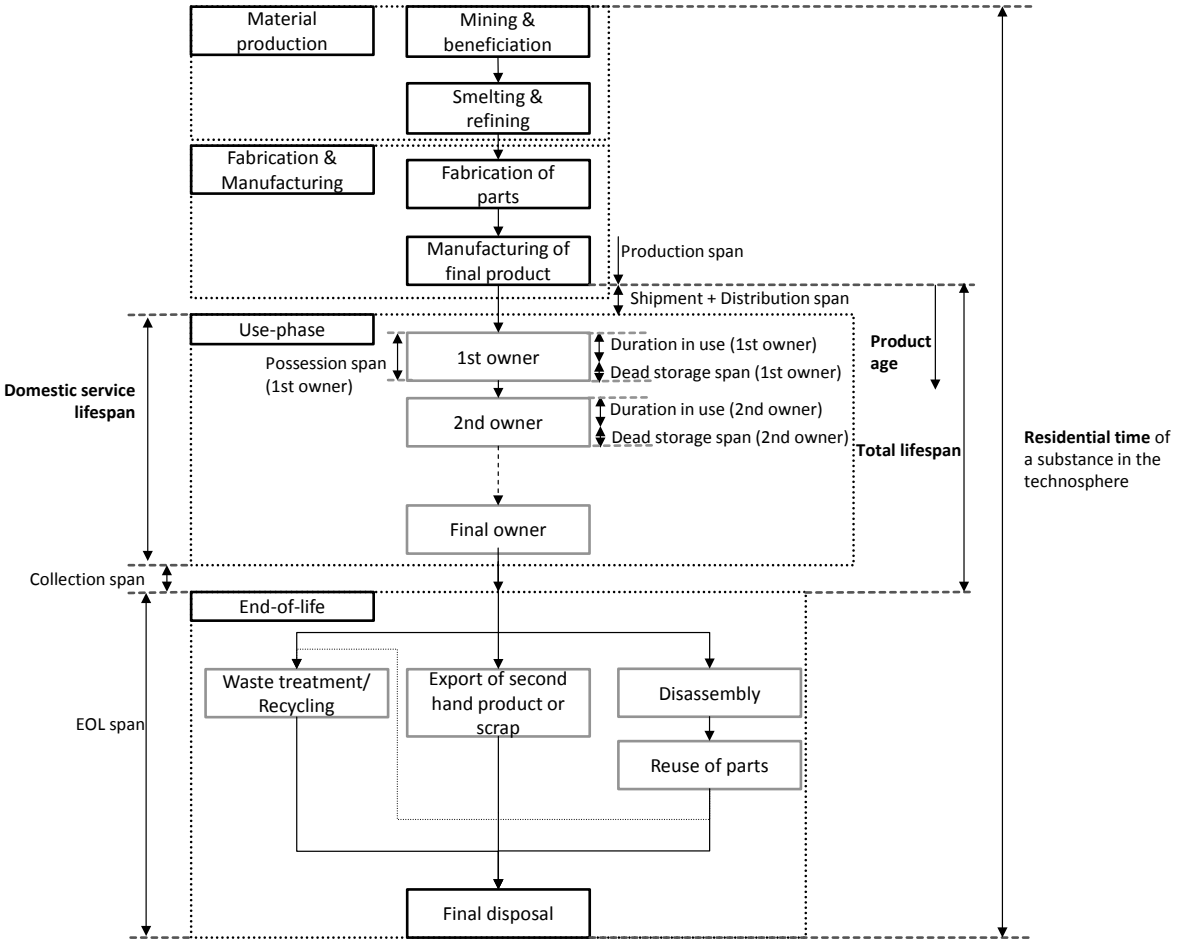


Figure 8: Different "spans" defining the life cycle (adapted from Murakami et al. 2010)

In MFA, the time spans of production, fabrication and manufacturing, retail inventory storage, and end-of-life are commonly assumed to be zero (Müller et al. 2014), which can be considered appropriate for the goals of most MFA studies, which usually focus on the use phase. As shown in Figure 8, material recycling (and reuse in other products), export (of second hand products or scrap), and reuse of parts are included in the EOL phase. They might, however, show spans of a magnitude that might pose the question whether the assumption of the EOL span being zero is appropriate. For studies that aim at modeling the fate of materials connected with the use of specific products (i.e. product-centric studies) this assumption ($EOL\ span = 0$) is still appropriate, as the flows of recycled material and their reuse (in other industrial systems) are accounted for in the lifecycle of other products and therefore are located outside the system boundaries. The consideration of these flows is described in section 4.6.

The time required for shipment and distribution as well as for collection is also commonly neglected in dynamic MFA studies (Müller et al. 2014), and correspondingly the total lifespan can be considered equal to the domestic service lifespan. The latter is therefore most commonly used in MFA studies, and a lot of available data refers to the domestic service lifespan (Murakami et al. 2010). In the following, the term "lifespan" will be used synonymously with "domestic service lifespan" and "total lifespan" unless otherwise noted.

Lifespan data on products in general is usually only sparsely available. Besides publications dealing with lifespans of single products or product groups especially from the field of reliability engineering, the Lifespan database for Vehicles, Equipment, and Structures (LiVES) (NIES 2010) of the Japanese National Institute for Environmental Studies needs to be highlighted as one major source of lifespan data. Lifespan data from various projects and publications is collected in this database (for details on LiVES see also Murakami et al. 2010).

The means of collecting lifespan data are important and need to be considered when dealing with such data. Direct observations of the products' lifespans are only seldom performed and are often hardly possible with buildings being one exception allowing for straightforward direct observations. Thus, other means to determine product lifespans are applied, including customer surveys (as described in Murakami et al. 2010), data from reliability engineering (see for example Sharma, Rana, and Gupta 2010 for reliability data on photovoltaic cells), direct sampling of EOL products (as for example used by Gößling-Reisemann, Knak, and Schulz (2009) for a variety of electronic products and by Polák and Drápalová 2012 for mobile phones), official statistics (as available for cars, e.g., used in Zimmermann and Gößling-Reisemann 2014b), and data from other literature. Every method has its specific features that need to be considered when deriving lifespans to be used in a model. In customer surveys, respondents can only provide information on their possession span and information regarding a possible second or third life may not be available. Data from reliability engineering covers aspects like mechanical failures and their likelihood over time while aspects like dead storage spans etc. are not considered. Direct samplings provide a good picture of the composition of EOL waste, but –depending on the respective products– limitations arise from uncertainties regarding the time and magnitude of shipment that might be unknown[30] and the age of the technology[31]. Statistics might have their specific drawbacks, e.g., the statistics of the German Federal Motor Transport Authority (Kraftfahrtbundesamt, KBA) provide information on de-registrations of cars which does not necessarily equals the number of cars at EOL, since a later re-registration is possible. These limitations need to be considered when using lifespan data in an MFA model, however, their actual relevance varies depending on the respective product; e.g., hibernation is particularly relevant for mobile phones (dead storage span of over 4 years, Polák and Drápalová 2012) and, thus, data from reliability engineering should be treated appropriately. Whereas data from reliability engineering will be more directly usable when dealing with products that are replaced right after they stop to function.

Besides the diversity in nomenclature and the specifics of the different means of collecting lifespan data, additional complexity arises from the fact that lifespans among individual products within a "population" of products will vary, at least for most commodities and structures. If available, lifespan data will usually refer to the average lifespan, but in many cases the distribution of lifespans within

[30] For products that have been sold only for a small period in time like it is the case for some small electronic devices this might not be an issue while other products are sold over a couple of years.

[31] E.g., EOL samplings of young technologies such as thin-film photovoltaics are not suited to derive conclusions regarding lifespan distributions. The vast majority of thin-film photovoltaic cells placed on the market since their initial market introduction will not be discarded for years and EOL sampling will not provide sound data.

this group of products will provide additional information that can be quite valuable for some purposes.

Two different approaches, the parametric and the non-parametric approach, can be used to estimate lifespan distributions. The non-parametric approach does not assume any statistical distribution and appears to be of little relevance for dynamic MFA studies (Oguchi et al. 2010). The parametric approach assumes a statistical distribution of lifespan data, such as the normal distribution, log-normal distribution, or Weibull distribution. To describe the temporal dynamics of MFA models, different quantitative measures originating from the field of reliability engineering can be used. Although concepts and mathematics from reliability engineering are almost directly applicable in dynamic MFA, some conceptual differences need to be taken into account. The main difference is that reliability engineering aims at evaluating, measuring, and predicting the reliability of a system in terms of its point of failure. In dynamic MFA, on the other hand, the point of discard (i.e. the point of entering the EOL stage assuming the collection span is zero, see "spans" definitions given above) is of interest. Especially for industrial goods, both, point of failure and point of discard, may be close to identical while for many consumer goods (e.g., small electrical and electronic equipment such as mobile phones, notebooks, USB-sticks) they may vary quite significantly. Thus, in the following, the term "discard" is used instead of "obsolescence" or "failure" which is used in reliability engineering although many dynamic MFA studies do not bother to differentiate.

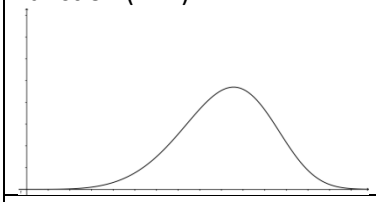
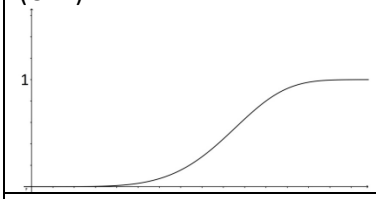
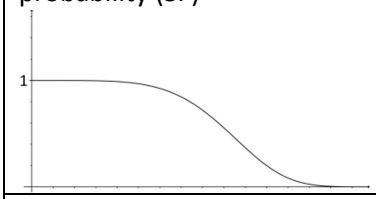
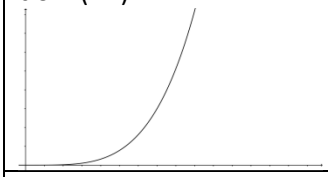
The selection of the lifespan distribution is an important step in the modeling process. For some products assuming an immediate discard after an average lifespan $\bar{T}$ might be appropriate (i.e. assuming a simultaneous exit function). For many other products, though, other types of lifespan distributions might prove to be more appropriate. Here, however, assuming that the probability of discard (i.e. the discard rate) remains constant with proceeding product age, i.e., assuming no aging effects occur (which results in an exponential distribution, see section 4.4.2), will be inappropriate for most products, and other functions are better suited. Especially the Weibull function[32] has been proven to provide accurate approximations of product lifespan distributions (see, e.g., OECD 2001; Tasaki et al. 2004; Oguchi et al. 2008; Murakami et al. 2010; Oguchi et al. 2010). Besides the Weibull function (described in detail in section 4.4.4), the normal and lognormal function, which are described with their respective characteristics and weaknesses in section 4.4.3, are used in MFA studies to model discard patterns with discard rates that increase over time.

Against this background, the simultaneous exit (SE) function, the normal and lognormal function, and the Weibull function are described in the following with a focus on the Weibull function due to its higher relevance in the modeling of product discard patterns. Before doing this, some terms and notations used throughout the text are specified in Table 10. In addition, the term "vintage", which is commonly used to described age structures of goods (e.g., Davidsdottir and Ruth 2004; Ruth and

[32] See Table 10 for an overview of different terms and notations of lifespan distribution functions.

Amato 2002), needs to be introduced. In this regard, products placed on the market in the same year are referred to as products of the same vintage.

Table 10: Terms and notations in lifespan modeling (cf. Gaede 1977; Barlow and Proschan 1978; Gertsbakh 1989; Melo 1999; Rausand and Høyland 2004; Müller et al. 2014; Bain 1978; Oguchi et al. 2010; Nomura 2005)

Term	Description	Notation
Lifespan probability density function (PDF) 	The PDF describes the relative likelihood for a product to reach a given maximum lifespan. It can also be interpreted as the distribution of maximum lifespans of products of the same vintage.	$f(t)$
Lifespan distribution function (CDF) 	Also referred to as cumulative PDF (CDF); it describes the probability that the time of discard is sooner than some given time t. It can also be interpreted as the share of discarded products of the same vintage.	$F(t)$
Survival function/ survival probability (SF) 	The SF describes the probability that the time of discard is later than some given time t (probability that the product is not discarded in the interval [0,t]); it can also interpreted as the share of products of the same vintage still in-use at time t.	$R(t) = 1 - F(t)$
Discard rate or hazard function (HF) 	The HF describes the probability that the time of discard is at time t and is defined as $f(t)/R(t)$; it can be interpreted as the probability of failure in the time interval [t,t+dt], given that the item has survived until time t.	$h(t) = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{R(t)}$
Mean time to discard (MTTD)	Also: mean; expectation $E(T)$ or average lifespan T_{avg}. The MTTD is the average time a product will spend in the use phase.	$E(T) = \int_0^\infty t f(t) dt$
Scale parameter	The scale parameter determines the scale (or unit) of measurement of the distribution and compresses or expands the associated distribution without altering its basic form.	λ
Shape parameter	The shape parameter determines the basic form or shape of a distribution within a given family of distributions.	k

One characteristic of probability density functions needs to be highlighted. Principally, in lifespan modelling, PDFs should fulfill the following condition:

$$\int_0^\infty f(t)\,dt = 1$$

Some functions, however, like the normal function, do not fulfill this criterion as further described in section 4.4.3. Furthermore, it needs to be said that there are no negative lifespans, and correspondingly –in lifespan modelling– the functions are only defined for $t \geq 0$.

4.4.1 Simultaneous Exit Function/ Dirac

A rather simple case of lifespan distributions is given in the case when a simultaneous discard of all products from the same vintage after an average product lifespan T_{avg} is assumed. Due to this "simultaneous exit" of the products, this distribution is also referred to as simultaneous exit (SE) function.

The SE function can also be interpreted as a special case of the delta function[33] $\delta(T - T_{avg})$ (also referred to as "Dirac" function) with a PDF that is zero everywhere except at $t = T_{avg}$. The integral of the Dirac function is 1. Figure 9 exemplarily shows PDF and SF of the simultaneous exit function.

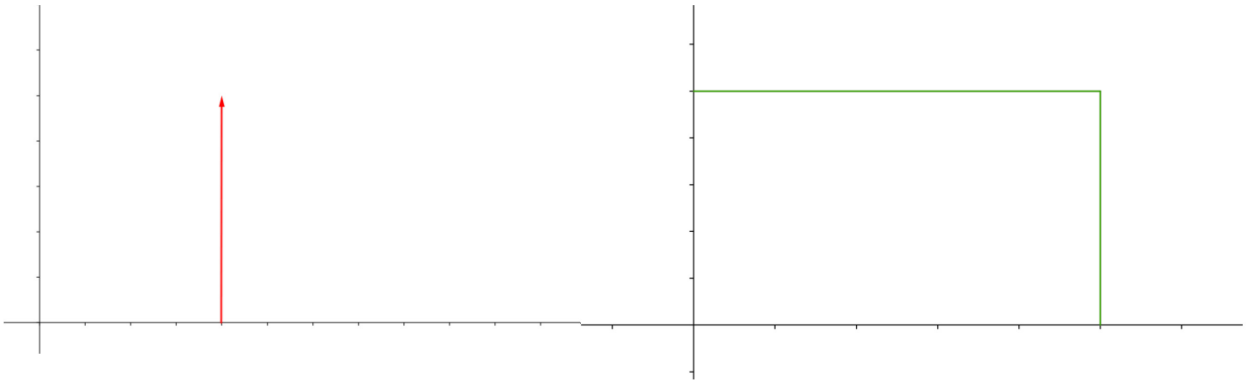


Figure 9: PDF (left) and SF (right) of SE/Dirac function

By some authors the SE function is recognized to be the most inappropriate function to model product lifespans (e.g., Nomura 2005; Law 2007). This might be the case within reliability engineering where product failure is modelled (a group of products that fail exactly after the same period of time is indeed rather unlikely). For modelling discard patterns of products, however, there might be cases where assuming a simultaneous exit might just be in line with the goal and scope of the study. This might be the case, for example, for components or manufacturing equipment that are replaced after a fixed period in time regardless of the occurrence of a failure. In these cases the actual discard patterns might come close to a simultaneous exit function.

4.4.2 Exponential Distribution

Among the approaches used to describe more complex distributions of product lifespans than a simultaneous exit, a rather simple case is given when no aging effects occur and the discard rate remains constant. This results in the exponential distribution which is the only lifespan distribution function with a constant discard rate (Gaede 1977; Barlow and Proschan 1978). This characteristic (the re-

[33] Strictly spoken, it is not a function, though.

maining life being independent of the current age) of the exponential distribution is also referred to as the "memoryless property" (Barlow and Proschan 1975; Gertsbakh 1989).

For modelling the discard patterns of products, the assumption of a constant discard rate is rather inadequate. However, the exponential function is of relevance for the distributions with non-constant discard rates such as the Weibull and the normal function. Therefore, a brief description of the mathematics of the exponential distribution is given in Table 11 (based on Gaede 1977; Barlow and Proschan 1978) and an exemplary visualization of the PDF and CDF is given in Figure 10.

Table 11: Mathematical description of the exponential distribution

PDF (see Figure 10)	$f(t,\lambda) = \lambda e^{-\lambda t}$
CDF	$F(t,\lambda) = 1 - e^{-\lambda t}$
SF	$R(t) = 1 - F(t) = e^{-\lambda t}$
HF	$h(t) = \frac{f(t)}{R(t)} = \frac{\lambda e^{-\lambda t}}{e^{-\lambda t}} = \lambda$

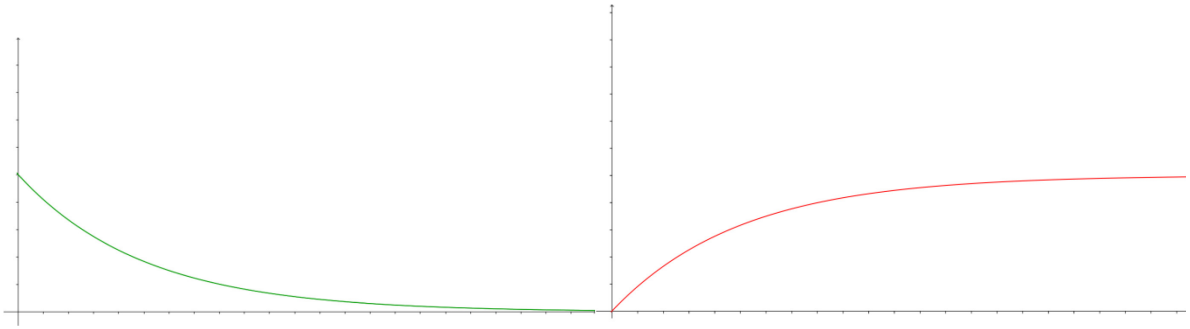


Figure 10: PDF (left) and CDF (right) of exponential distribution

4.4.3 Normal and Lognormal

Generally, the normal (or Gaussian) distribution is a widely used statistical model, and empirical evidence indicates that it provides a good representation for many physical phenomena including examples such as errors of various types, average temperature in a given area, and scores on an intelligence test (Melo 1999). It is also used for lifespan modelling, and examples for its application to dynamic MFA can be found in (Müller, Wang, and Duval 2011; Müller et al. 2007; Müller 2006; Müller, Bader, and Baccini 2004).

The normal distribution is symmetric about its mean μ which can also be considered as the location parameter[34]. It is further characterized by its standard deviation σ which is equivalent to the scale parameter. The range of variation of the normal (or Gaussian) distribution function ranges from minus to plus infinity, which –in dynamic MFA– would mean that there is a non-zero probability for

[34] In contrast to the location parameter of the Weibull distribution (see section 4.4.4) that determines the point in time where discard/failure starts (guaranteed lifetime), the location parameter of the normal distribution determines its mean.

negative lifespans of products (Melo 1999). Therefore, the practical relevance of the normal distribution in dynamic MFA is limited.

Addressing this disadvantage of the normal distribution, two alternative distributions, the truncated normal distribution and the lognormal distribution can be used. The introduction of a in the PDF of the truncated normal distribution (see Table 12) ensures that $\int_0^\infty f(t)dt = 1$ (cf. section 4.4), so f is the density of a non-negative lifespan. For $\mu \gg 3\sigma$ a is ≈ 1 and can be omitted for most practical cases (Barlow and Proschan 1978). The truncated normal distribution has been found to provide a good fit for failure patterns of various items by Davis (1952) (in Barlow and Proschan 1975). More common than the truncated normal distribution in MFA modeling is, however, the lognormal distribution. The lognormal distribution is commonly used for analysis of cycles-to-failure in fatigue modeling, material strengths, particle size distribution in powders, etc. (Dahlström et al. 2004). It provides a better approximation of the discard behavior of some material stocks with long lifespans (e.g., the residential building stock) than a normal distribution (Pauliuk, Wang, and Müller 2012). The respective equations (Barlow and Proschan 1975; Barlow and Proschan 1978) are given in Table 12, an exemplary visualization of PDF and SF of the lognormal distribution is given in Figure 11.

Table 12: Mathematical description of normal distribution, truncated normal distribution and log-normal distribution

PDF, normal distribution	$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(t-\mu)^2}{2\sigma^2}}$
PDF, truncated normal distribution	$f(t) = \frac{1}{a\sigma\sqrt{2\pi}} e^{\frac{-(t-\mu)^2}{2\sigma^2}}$ with $\sigma > 0, -\infty < \mu < \infty, a = \int_0^\infty (1/\sigma\sqrt{2\pi}) e^{(-\frac{(t-\mu)^2}{2\sigma^2})}\, dt.$
PDF, lognormal distribution	$f(t) = \frac{1}{t\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\ln t-\mu}{2\sigma^2}\right)^2}$

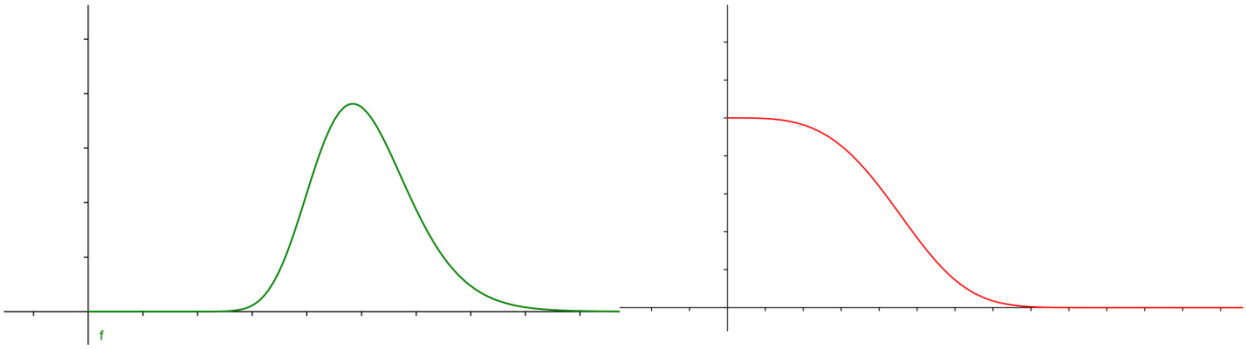


Figure 11: PDF and survival function of lognormal distribution

4.4.4 WEIBULL DISTRIBUTION

The Weibull distribution –more precisely referred to as family of distributions– has been found to give a good approximation of product lifespans and is one of the most commonly used distributions to model discard patterns of products (cf. Müller et al. 2014; Oguchi, Tasaki, and Moriguchi 2010; Oguchi et al. 2008; Kagawa, Tasaki, and Moriguchi 2006; Tasaki et al. 2004; OECD 2001; Gertsbakh 1989; Barlow and Proschan 1978) basically due to its flexibility and ability to accommodate many different types of distribution. It covers cases of increasing as well as well decreasing discard rates as well as the exponential distribution and is well suited to approximate various distributions. It exists in two different versions, three-parametric and two-parametric. The three-parametric Weibull PDF can be defined as given in Table 13 (see, e.g. Rausand and Høyland 2004).

Table 13: Mathematical description of three-parametric Weibull distribution

PDF, three parametric Weibull distribution	$f(t,\lambda,k,\theta) = \lambda k(\lambda(t-\theta))^{k-1}e^{-(\lambda(t-\theta))^k}$
CDF, three parametric Weibull distribution	$F(t,\mathrm{k},\lambda,\theta) = 1 - e^{-(\lambda(t-\theta))^k}$
with	
product age	t
Weibull shape parameter	k
Weibull scale parameter	λ
location parameter	θ

Another also quite common notation of the three-parametric Weibull PDF is (see, e.g., Lehman 1963)[35]:

$$f(t,\beta,k,\theta) = k\beta^{-k}(t-\theta)^{k-1}e^{-\left(\frac{t-\theta}{\beta}\right)^k}$$

Here, the scale parameter is β which is equivalent to $\frac{1}{\lambda}$ in the other notation. However, in the following, the notation given in Table 13 and Table 14 will be used as well as its corresponding definition of the scale parameter. The location parameter θ can also be described as the guaranteed lifespan (Lehman 1963), i.e., products do not leave the use phase until a particular point in time (θ) is passed. For most commodities this does not make sense and $\theta = 0$ can be assumed[36]. Thus, the two-parametric Weibull PDF, lifespan distribution function, survival function and discard rate function are

[35] The respective notation of the two-parametric Weibull PDF (e.g., Nomura 2005) is

$$f(t,\beta,k) = \frac{k}{\beta^k}t^{k-1}e^{-\left(\frac{t}{\beta}\right)^k}$$

[36] In fact, for most products a certain time passes before they are discarded; for many products this "guaranteed lifespan" will be in the range of a few days to a few weeks (e.g., household supplies), or up to several months. Considering the "guaranteed lifespan" makes only sense, though, if the guaranteed lifespan is particularly long and the analysis relatively detailed regarding the considered intervals in time.

obtained (cf. Barlow and Proschan 1975; Gaede 1977; Barlow and Proschan 1978; Gertsbakh 1989) (see Table 14).

Table 14: Mathematical description of the two-parametric Weibull distribution

PDF	$f(t,\lambda,k) = \lambda k(\lambda t)^{k-1} e^{-(\lambda t)^k}$
CDF	$F(t,\mathrm{k},\lambda) = 1 - e^{-(\lambda t)^k}$
SF	$R(t,\mathrm{k},\lambda) = 1 - F(t,k,\lambda) = e^{-(\lambda t)^k}$
HF	$h(t) = \frac{f(t)}{R(t)} = \frac{\lambda k(\lambda t)^{k-1} e^{-(\lambda t)^k}}{e^{-(\lambda t)^k}} = k\lambda(\lambda t)^{k-1}$

The scale parameter λ –as described in Table 10– compresses or expands the Weibull distribution without altering its basic form which is determined by the shape parameter k (sometimes also referred to as slope parameter). The shape parameter is a key feature of the Weibull distribution, and the properties of the Weibull distribution are much more influenced by changes in the shape parameter than a change in scale or –in the three-parametric case– location parameter (Melo 1999).

For values of $k < 1$ the distribution becomes a so-called DFR (decreasing failure rate)-distribution, i.e., the discard rate described by the hazard function decreases over time. For values of $k > 1$ it becomes an increasing failure rate (IFR) distribution, i.e., the discard rate increases over time. For $k = 1$ it becomes equal to the exponential distribution[37] (see Table 11). Thus, the shape parameter allows applying the Weibull function to any phase of the so-called bathtub curve (Ooi, Kassim, and Demidenko 2007; Wilker 2010). The bathtub curve represents the idea that the discard behavior of products of the same vintage can be viewed as comprised of three distinct periods, a period of infant mortality, a period of random failures, and a period of wear out (Wilker 2010; Klutke, Kiessler, and Wortman 2003). It is constructed by applying different k-values for the different periods, which results in three distinct PDFs, CDFs, and HFs. To model infant mortality, a shape parameter of $k < 1$ can be chosen. For constant discard rates it is $k = 1$ and for aging effects (wear out) it is $k > 1$ (see Figure 12). With further increasing k values the discard rate function rises more steeply, and the PDF becomes more peaked (examples for Weibull PDFs resulting from different k values and Weibull SF and CDF are given in Figure 13).

[37] $h_{k=1}(t) = \lambda \cdot 1 \cdot (\lambda t)^{1-1} = \lambda$
$f_{k=1}(t,\lambda,k) = \lambda \cdot 1 \cdot (\lambda t)^{1-1} e^{-(\lambda t)^1} = \lambda e^{-\lambda t}$

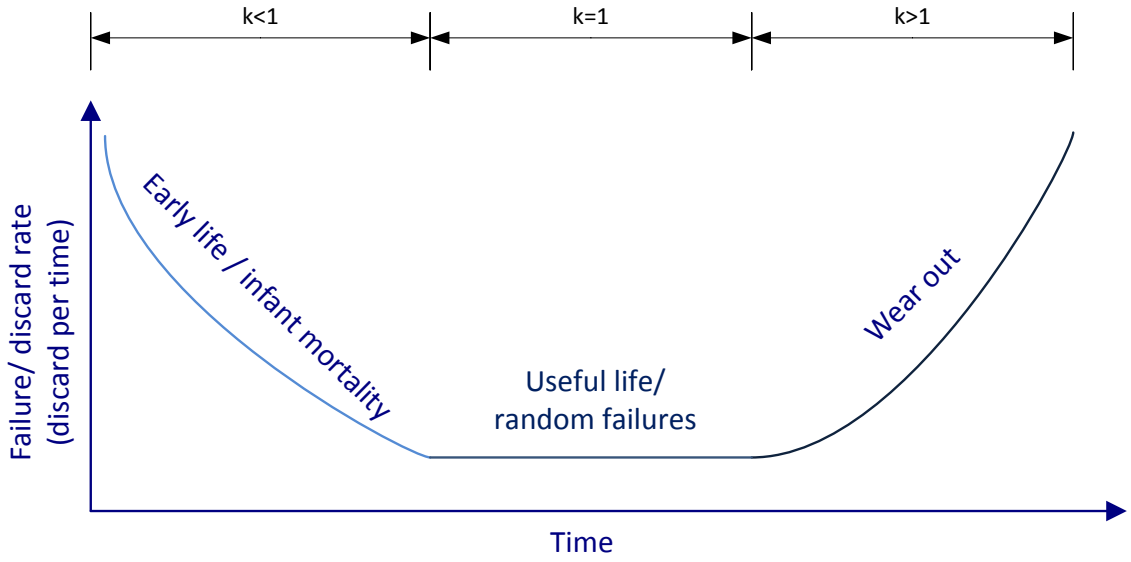


Figure 12: Shape parameter and bathtub curve

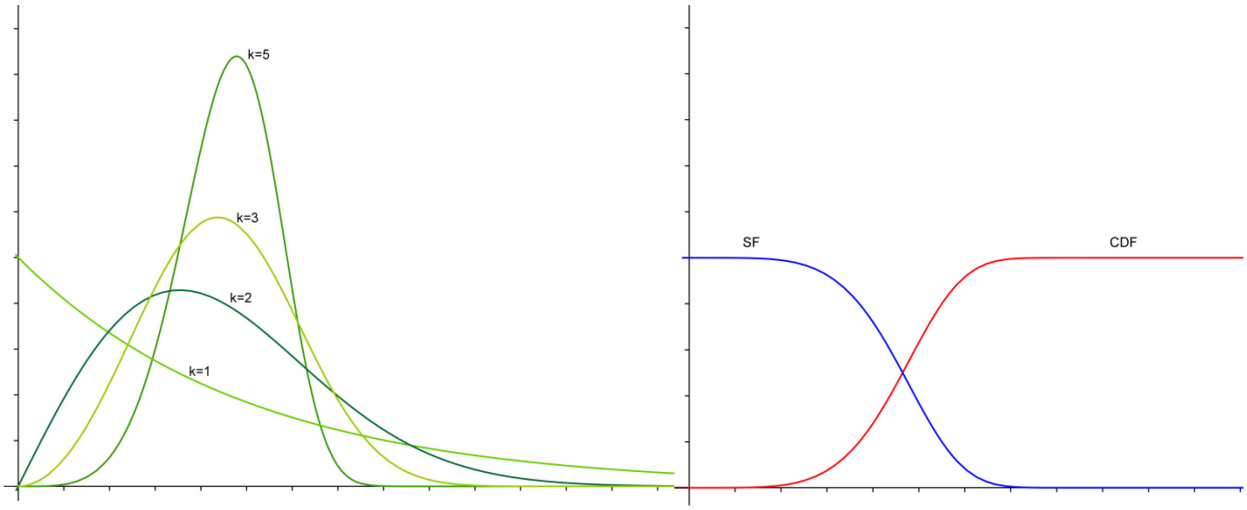


Figure 13: Weibull PDFs for different shape parameters (left) and Weibull SF and CDF (right)

Still, mixed Weibull distributions with different sub-populations of $k < 1$, $k = 1$, and $k > 1$ that result in the bathtub curve are hardly ever applied in the modelling of discard patterns. For most products or commodities wear out is the dominant effect describing their discard patterns, and reported k values vary between 1 and 5 (cf. OECD 2001; Nomura 2005; Oguchi et al. 2008; NIES 2010). In such cases, i.e., infant mortality is not particularly distinct, and constant discard rates are not to be applied, the Weibull function is well suited to model product lifespans without further differentiation of sub-populations. Klutke, Kiessler, and Wortman (2003) even discourage from the application of the bathtub curve for cases with more distinct infant mortality.

Even though the IFR property (meaning $k > 1$) cannot always be guaranteed, intuition and engineering experience often suggest that the average remaining lifetime of on older product should be smaller than that of a brand new product (Gertsbakh 1989).

Some further general statements can be made regarding the shape parameter k (OECD 2001; Dubey, Sat Ya D. 1967):

- $1 < k < 2$ → risk of discard increases with age but at a decreasing rate/wear-out-failure;
- $k = 2$ → risk of discard increases linearly;
- $k > 2$ → risk of discard increases progressively;
- $k = 3.60232$ → approximation of the normal distribution;
- $k \gg 5$ → approximation of a simultaneous exit function.

An interesting property of the Weibull distribution is given by the fact that the probability of surviving $\frac{1}{\lambda}$ years (or more generally time units) is

$$R\left(t = \frac{1}{\lambda}\right) = 1 - F\left(t = \frac{1}{\lambda}, k, \lambda\right) = \frac{1}{e} = 0.368\ldots$$

This characteristic is independent of the two parameters k and λ[38]. The time span $\frac{1}{\lambda}$, i.e., the inverse of the scale parameter and the timespan after which about 63.2% of the products have been discarded, is also referred to as the characteristic lifespan T_{ch}[39] (cf. Lehman 1963; Wilker 2010).The mean $E(t)$ of the Weibull PDF (i.e. the average lifespan T_{avg}) is given as (see, e.g., Gaede 1977; Nomura 2005; Wilker 2010):

$$E(t) = T_{avg} = \frac{1}{\lambda}\Gamma\left(1 + \frac{1}{k}\right) = T_{ch}\Gamma\left(1 + \frac{1}{k}\right)$$

Γ is the gamma function that is given as (Gaede 1977):

$$\Gamma(x) \coloneqq \int_0^\infty e^{-y} y^{x-1} dy$$

$$\Gamma(x+1) = x\Gamma(x)$$

$$\Gamma(n+1) = n! = 1 \cdot 2 \cdot \cdots n \text{ for } n = 1,2,3,\ldots$$

Γ is available tabulated (e.g., in Wilker 2010) and, thus, using the relation given above, T_{ch} and λ can be calculated based on the average lifespan T_{avg} and the shape parameter k:

$$\lambda = \frac{1}{T_{ch}} = \frac{\Gamma\left(1 + \frac{1}{k}\right)}{T_{avg}}$$

[38] It is also valid for the three-parametric Weibull function as the probability of surviving $\frac{1}{\lambda}$ time units beyond θ.

[39] For the three parameter Weibull distribution it is $T_{ch} = \frac{1}{\lambda} + \theta$.

Average lifespan T_{avg} and the shape parameter k are available in databases and publications for many different products (e.g., Nomura 2005; Oguchi et al. 2008; NIES 2010). However, especially for non-consumer goods there appears to be significantly less data and in such cases other sources need to be consulted and assumptions need to be made as described in the analysis of the case studies in section 5.

4.4.5 Implementation of Lifespan Distributions into MFA Models

As described at the beginning of section 4, MFA is about analyzing the flows of materials or substances, respectively, through industrial systems. These flows can be described as shown in Figure 14 and further explained in Table 15.

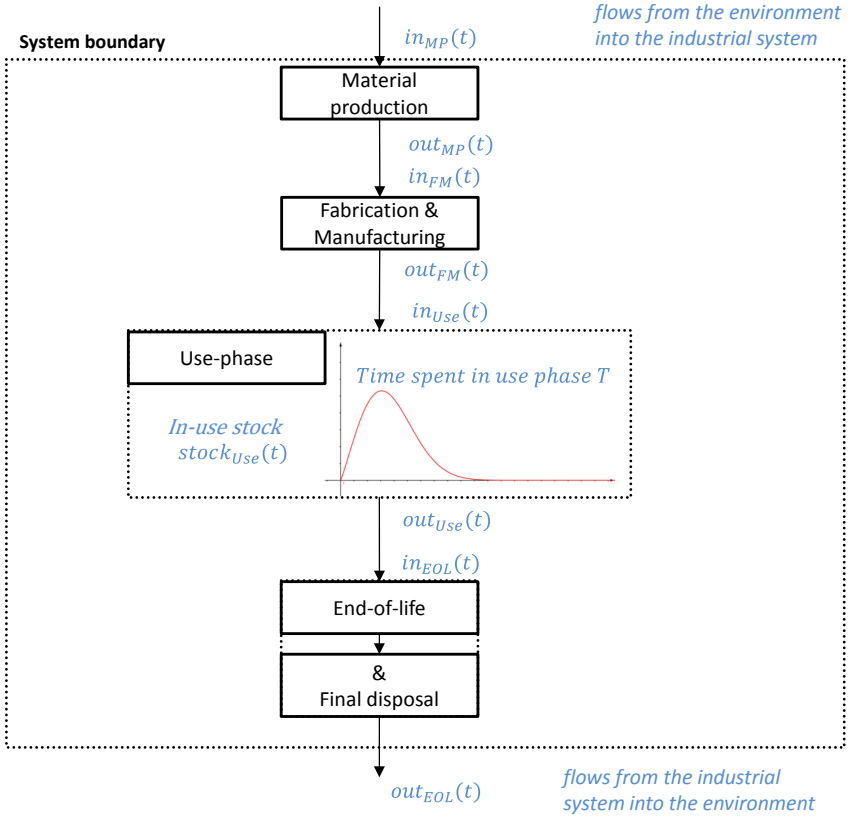


Figure 14: Material flows through an industrial system

Table 15: Notations of stocks and flows in an industrial system

Flow	Notation	Dimension
Input flow into material production (material taken from the environment) at time t.	$in_{MP}(t)$	Mass/time
Output flow of material production and input flow to fabrication and manufacturing at time t.	$out_{MP}(t) = in_{F\&M}(t)$	Mass/time
Output flow of fabrication and manufacturing and input flow to use phase at time t.	$out_{F\&M}(t) = in_{Use}(t)$	Mass/time
Output flow of use phase and input flow to end-of-life at time t.	$out_{Use}(t) = in_{EOL}(t)$	Mass/time
Output flow of EOL (incl. final disposal) into environment at time t.	$out_{EOL}(t)$	Mass/time
Stock in use phase at time t.	$stock_{Use}(t)$	Mass

Through the assumption of the time spent in material production and fabrication and manufacturing being zero (see section 4.4), the flow entering the industrial system at time *t* enters the use phase at the same point in time (minus losses and potential recycled shares of production waste/scrap as described in section 4.6). The output flows from the use phase, however, occur only with some delay, described by the lifetime distribution function. The relationship between input flow and output flows mathematically corresponds to a convolution and can be expressed via $*$ as in Table 16 (cf. Müller et al. 2014):

Table 16: Relation between input and output flows

$$out_{Use}(t) = (in_{Use}{}^{*} f)(t) = \int_{0}^{\infty} in_{Use}(t-u) \cdot f(u)\, du$$

with $f(t)$ being the PDF of the lifetime distribution function. I.e. the output flows at *t* are calculated based on the historic input flows and their respective PDF values. Historic input flows are considered reaching back to $-\infty$ (in practice to the year of the first introduction to the market) until the present time, as reflected in the boundaries of the interval. In fact, due to data availability, this will not always be feasible, and different simplified approaches are possible including applying cut-off criteria for "very early" years (as used, for example, in Zimmermann and Gößling-Reisemann 2014b) and assuming constant stocks with homogenous age distributions (as done, for example, in Zimmermann and Gößling-Reisemann 2014a). For the following lifecycle stage, end-of-life, the time span is, again, assumed to be zero.

4.4.6 DISCRETIZATION

So far, the explanations of calculating material stocks and flows using lifespan distribution functions referred to continuous cases. In fact, however, material stocks and flows are typically reported for discrete intervals with one year being a typically assessed interval in time (Müller et al. 2014; Murakami et al. 2010). This is justified by the goals of most studies which explicitly aim at quantifying

stocks and flows per year as well as it is caused by data availability (e.g., statistics often refer to discrete intervals of a length of one year). Input flows into use are calculated based on time series of the amounts of products placed on the market per year which often have a constant sampling rate of $\tau = 1$ year (cf. Zimmermann and Gößling-Reisemann 2015). Hence, the respective equations need to be discretized:

$$X[n] = \int_{n\tau}^{(n+1)\tau} x(t)dt$$

with $n = 1, 2, 3, \ldots$

I.e., instead of the continuous flows, the aggregated flows of one year are considered as one. The respective notations of input and output flows are given in Table 17.

Table 17: Continuous and discrete notations of stocks and flows

Flow	Continuous	Discrete
Input flow into life cycle stage XY at time t/n.	$in_{XY}(t)$	$In_{xy}[n]$
Output flow of life cycle stage XY at time t/n.	$out_{XY}(t)$	$Out_{xy}[n]$
Stock in use phase at time t/n.	$stock_{Use}(t)$	$Stock_{xy}[n]$

4.5 Synopsis: Approach for Product-Centric MFA

In the previous sections, the characteristics of dynamic MFA have been described. Based on this, in the following, an approach for the analysis of material flows connected with specific products and the corresponding data requirements will be described[40]. Subsequently, the additional consideration of dissipative losses and flows of recycled shares is described in sections 4.5.4 and 4.6.

4.5.1 Input Flow into Use Phase

The approach for product-centric MFA is built around the modelling of the use phase. The input flow into the use phase $in_{Use}(t)$ or $In_{Use}[n]$, respectively, is determined based on the amount of products placed on the market per year $a(t)$ and $A[n]$, respectively, –usually available as time series– and the concentration of the substance of interest per product $c(t)$ (i.e., its specific concentration). For some products the concentration $c(t)$ might indeed be a time dependent variable and will decrease or increase over time. Often, however, the change in concentration is either negligible or unknown, and $c(t)$ is assumed to be constant[41] ($c(t) = c = const.$).

[40] The approach for product-centric MFA has also been briefly described in some previously published articles (Zimmermann, Rehberger, and Gößling-Reisemann 2013; Zimmermann 2013a; Zimmermann and Gößling-Reisemann 2014a; Zimmermann and Gößling-Reisemann 2015).

[41] In these cases, resulting uncertainties can be dealt with by conducting sensitivity analyses and/or calculating with ranges.

The input flow into use is then calculated as

$$in_{Use}(t) = c \cdot a(t)$$
$$In_{Use}[n] = c \cdot A[n]$$
$$\text{with } A[n] = \int_{n\tau}^{(n+1)\tau} a(t)dt \text{ [42]}$$

4.5.2 Output Flows from Use Phase

The output flows from the use phase $out_{Use}(t)$ and $Out_{Use}[n]$, respectively, are calculated based on the input flows (see section 4.5.1) and the respective lifetime distribution as described in section 4.4.5. I.e.

$$out_{Use}(t) = (in_{Use}{}^{*} f)(t) = \int_0^{\infty} in_{Use}(t-u) \cdot f(u)\, du = \int_0^{\infty} c \cdot a(t-u) \cdot f(u)\, du$$

For the discrete case, the lifetime distributions need to be discretized following the equation given in Table 16, too. For the Weibull distribution, this results, for example, in the following equation which can be interpreted as the probability of a lifespan between n and $n+1$:

$$F[n] = \int_{n\tau}^{(n+1)\tau} \lambda k(\lambda t)^{k-1} e^{-(\lambda t)^k} dt = f\big((n+1)\tau\big) - f(n\tau) = e^{-(\lambda n\tau)^k} - e^{-(\lambda(n+1)\tau)^k}$$

The discretization of the other lifetime distribution functions (e.g., lognormal, exponential) is conducted accordingly.

4.5.3 Stocks in Use Phase

The assessment of in-use stocks is an inherent part of the goals of most dynamic MFA studies as described in section 2.2. The stock development is given by the initial stock ($stock_{Use,init}$) and the net flows per year:

$$stock_{Use}(t) = stock_{Use,init} + \int_0^t in_{Use}(t)\ dt - \int_0^t out_{Use}(t)dt$$
$$Stock_{Use}[n] = Stock_{Use,init} + \sum_0^n In_{Use}[n] - \sum_0^n Out_{Use}[n]$$

[42] As the amount of products placed on the market usually is only available as a time series with $\tau = 1$ year $A[n]$ is in fact not calculated based on $a(t)$ but directly taken from the data.

4.5.4 *Flows Connected with Other Life Cycle Stages*

As the input flow into the use phase is determined based on the underlying data (amount of products placed on the market $a(t)$ or $A[n]$, respectively, and the specific material concentration c, the flows in the previous life cycle stages are calculated on that basis.

Regarding the flows connected to fabrication and manufacturing, as said previously, it is

$$in_{Use}(t) = out_{FM}(t)$$
$$In_{Use}[n] = Out_{FM}[n]$$

The input flows into F&M are the output flows corrected by potential dissipative losses as well as scrap and production waste (see section 4.6 for further details on the consideration of dissipative losses and recycled shares), i.e., the difference between input and output flow includes dissipative losses as well as the recycled share of production scrap. Commonly, the relation of input and output flows of the fabrication and manufacturing stage is available in terms of data on production efficiencies $e_{FM}(t)$ and $E_{FM}[n]$, respectively, which are time dependent due to technological progress:

$$in_{FM}(t) = \frac{out_{FM}(t)}{e_{FM}(t)}$$
$$In_{FM}[n] = \frac{Out_{FM}[n]}{E_{FM}[n]}$$

The flows into and out of the material production stage are determined analogously to the fabrication and manufacturing stage. Here, however, the efficiency describes the extraction efficiency of metal from the raw materials, i.e., from the ore, and is notated as $e_{MP}(t)$ and $E_{MP}[n]$, respectively. The output flows equal the input flows into F&M and the input flows can be calculated as:

$$in_{MP}(t) = \frac{out_{MP}(t)}{e_{MP}(t)}$$
$$In_{MP}[n] = \frac{Out_{MP}[n]}{E_{MP}[n]}$$

4.6 Consideration of Dissipative Losses and Recycled Shares

In the described dynamic product-centric MFA approach, so far, (dissipative) losses and flows of recycled material from F&M as well as from the EOL phase have not been considered explicitly. In fact, dissipative losses occur at various different locations along the product (or material) life cycle, and reducing these losses is an integral part of a sustainable materials management as well as the hidden agenda of MFA (cf. sections 2.3, 3, and 4). Thus, analyzing dissipative losses should be part of any analysis in line with these goals, although there has been a lack of consistent methodology as well as

terminology, which is reflected in the studies that actually comprise a quantification of dissipative losses (cf. section 3).

The relevance of flows of recycled material has also been implied at the beginning of section 4.4. In F&M as well as during EOL, waste and scrap arise and are potentially recycled. In fact, recycling may occur in terms of material recycling as well as in terms of reuse of components and export of scrap products with potential reuse abroad. As indicated, in a product-centric analysis these flows can be considered losses from the system boundary (as the analysis focuses on the modeling of the fate of materials connected with a specific product) but still need to be quantified and considered in the calculation of the flows within the system as well as distinguished from dissipative losses. Regarding EOL and production scrap and waste, the recycling rates are of importance. Generally, the treatment of pre-consumer scrap shows relatively high recycling rates even for critical metals due to the higher purity and facilitated collection. The share that is not recycled needs to be considered as dissipative loss ("*there are only two possible fates for waste materials: recycling/reuse or dissipative loss*", Ayres and Simonis (1994), see chapter 3). For EOL waste, the (post-consumer) recycling rates of most critical metals appear to be near zero and thus, commonly, an almost complete dissipative loss can be assumed.

For the consideration of dissipative losses in the model, the definition and classification scheme described in section 3.4 is used, i.e., the approach differentiates between the life cycle stage in which the dissipative losses occur and the receiving medium (see Figure 5)[43]. In practice, however, modeling these losses is often impeded by data gaps and methodological complications.

Dissipative losses can be considered with loss or dissipation rates that describe the share of material lost in the respective life cycle phase in relation to the input flow. Another principally possible way to quantify dissipative losses is by leaching rates that describe the share of material dissipating per time unit in relation to the stock. As stocks are considered only in the use phase (since the time span of the other life cycle stages is assumed to be zero), this approach could be only applied to the use phase and, here, data availability barely admits such approaches. In fact, leaching factors are rarely applied (Müller et al. 2014), and data on loss or dissipation rates is more frequently available since these can be obtained from observations of input and output flows. The approach described in the following is based on the use of dissipation rates to quantify dissipative losses.

The dissipative losses from the stages of material production and dissipative losses and recycled shares from F&M are shown in Figure 15 for the continuous as well as the discrete case, with the respective notations explained in Table 18.

[43] The approach has been described in outline in (Zimmermann and Gößling-Reisemann 2015).

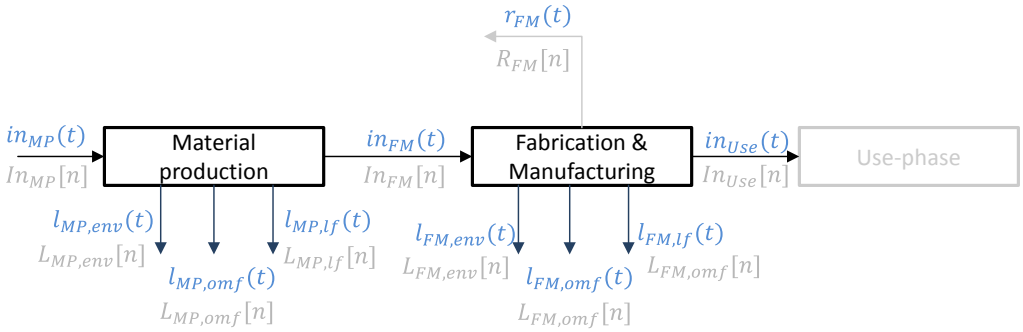


Figure 15: Dissipative losses from material production, fabrication and manufacturing

Table 18: Continuous and discrete notations of dissipative losses from production and F&M and related flows

Item	**Notation (continuous)**	**Notation (discrete)**
Total dissipative losses from material production	$l_{MP}(t)$	$L_{MP}[n]$
- Losses from MP to the environment.	$l_{MP,env}(t)$	$L_{MP,env}[n]$
- Losses from MP to other material flows.	$l_{MP,omf}(t)$	$L_{MP,omf}[n]$
- Losses from MP to landfills.	$l_{MP,lf}(t)$	$L_{MP,lf}[n]$
Recycled shares from F&M	$r_{FM}(t)$	$R_{FM}[n]$
Total dissipative losses from F&M	$l_{FM}(t)$	$L_{FM}[n]$
- Losses from F&M to the environment.	$l_{FM,env}(t)$	$L_{FM,env}[n]$
- Losses from F&M to other material flows.	$l_{FM,omf}(t)$	$L_{FM,omf}[n]$
- Losses from F&M to landfills.	$l_{FM,lf}(t)$	$L_{FM,lf}[n]$

The consideration of the losses in the calculation of the material flows into and out of the stages of material production, F&M and use can be conducted using the following equations:

$$in_{Use}(t) = out_{FM}(t) = in_{FM}(t) - (l_{FM}(t) + r_{FM}(t))$$
$$In_{Use}[n] = Out_{FM}[n] = In_{FM}[n] - (L_{FM}[n] + R_{FM}[n])$$
$$in_{FM}(t) = out_{MP}(t) = in_{MP}(t) - l_{MP}(t)$$
$$In_{FM}[n] = Out_{MP}[n] = In_{MP}[n] - L_{MP}[n]$$
$$l_{FM}(t) = l_{FM,env}(t) + l_{FM,omf}(t) + l_{FM,lf}(t)$$
$$L_{MF}[n] = L_{FM,env}[n] + L_{FM,omf}[n] + L_{FM,lf}[n]$$
$$l_{MP} = l_{MP,env} + l_{MP,omf} + l_{MP,lf}$$
$$L_{MP}[n] = L_{MP,env}[n] + L_{MP,omf}[n] + L_{MP,lf}[n]$$

Furthermore, the efficiency of material production and F&M e_{MP}/E_{MP} and e_{FM}/E_{FM}, respectively (see section 4.5.4), can be expressed as:

$$\frac{out_{MP}(t)}{in_{MP}(t)} = e_{MP}(t) = 1 - l_{MP}(t)$$
$$\frac{Out_{MP}[n]}{In_{MP}[n]} = E_{MP}[n] = 1 - L_{MP}[n]$$
$$\frac{out_{FM}(t)}{in_{FM}(t)} = e_{FM}(t) = 1 - \left(l_{FM}(t) + r_{FM}(t)\right)$$
$$\frac{Out_{FM}[n]}{In_{FM}[n]} = E_{FM}[n] = 1 - (L_{FM}[n] + R_{FM}[n])$$

In this context, $\frac{L}{In}$ can also be referred to as the dissipation rate indicating the share of input material dissipating in the respective process stage. Dissipation rates are also used for the assessment of dissipative losses from the use phase. In reality, for most product application dissipation will be an ongoing process stretched over the use span of the product, possibly including the dead storage span as well. Here, dissipation might be uniformly distributed or its rate may increase or decrease over time (or correspond to any type of random distribution). Data on these dynamics will, however, hardly ever be available and to the author's knowledge no studies assessing these dynamics have been conducted so far. In addition, the assessment of these dynamics would not provide any additional benefit considering the goals of most MFA studies, and thus a simplified approach neglecting the dynamics of in-use dissipation can be considered sufficient (cf. Zimmermann and Gößling-Reisemann 2015).

This discrete consideration of the dissipative losses is principally possible at any point in time during the product lifespan. The quantification of the stock is usually conducted with regard to potential material recovery, though, and considering dissipative losses not at the beginning of the use phase would lead to an overestimation of the material stock that will eventually result in a secondary material flow. Hence, the dissipative losses are considered at the time the input flows enter the use phase.

The share of the input flow dissipating into the different media is described by the dissipation tor d, or, respectively, d_{env} (dissipation factor for dissipation into the environment), d_{omf} (dissipation factor for dissipation into other material flows), and d_{lf} (dissipation factor for dissipation to landfills) with

$$d = d_{env} + d_{omf} + d_{lf}$$

These factors might be considered constant over time but might vary, too[44]. Hence, the losses from use phase are calculated as

$$l_{use}(t) = in_{use}(t) \cdot d(t)$$
$$L_{Use}[n] = In_{Use}[n] \cdot D[n]$$
$$l_{use,env}(t) = in_{use}(t) \cdot d_{env}(t)$$
$$L_{Use,env}[n] = In_{Use}[n] \cdot D_{env}[n]$$

[44] I.e. the equation needs to be transformed to $d(t) = d_{env}(t) + d_{omf}(t) + d_{lf}(t)$

$$l_{use,omf}(t) = in_{use}(t) \cdot d_{omf}(t)$$
$$L_{Use,omf} = In_{use}[n] \cdot D_{omf}[n]$$
$$l_{use,lf}(t) = in_{use}(t) \cdot d_{lf}(t)$$
$$L_{Use,lf}[n] = In_{Use}[n] \cdot D_{lf}[n]$$

The notations are further explained in Table 19. In the EOL phase, again, the rule of Ayres and Simonis (1994) applies: "*there are only two possible fates for waste materials: recycling/reuse or dissipative loss*". I.e., besides dissipative losses the recycled share of the EOL material needs to be taken into account, as shown in Figure 16.

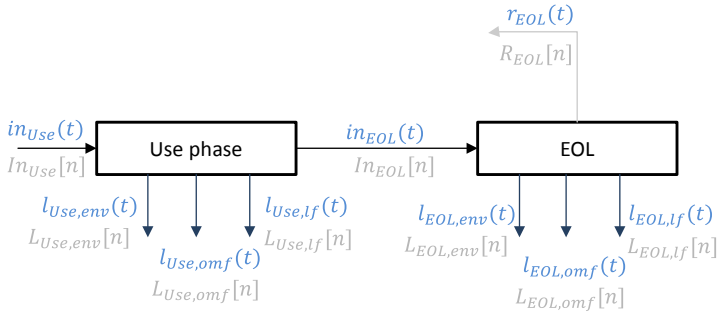


Figure 16: Dissipative losses from use phase and EOL

Losses from the EOL phase are calculated analogously to the losses from material production and F&M.

$$l_{EOL}(t) = l_{EOL,env}(t) + l_{EOL,omf}(t) + l_{EOL,lf}(t)$$
$$L_{EOL}[n] = L_{EOL,env}[n] + L_{EOL,omf}[n] + L_{EOL,lf}[n]$$

In addition to the dissipative losses the share of material that is recovered and recycling during EOL r_{EOL}/R_{EOL} needs to be taken into account. As the time spent in the EOL phase is considered to be zero, the following statement can be made regarding the input flows to EOL, dissipative losses, and recycled share:

$$in_{EOL}(t) = l_{EOL}(t) + r_{EOL}(t)$$
$$In_{EOL}[n] = L_{EOL}[n] + R_{EOL}[n]$$

The main flows of the described approach for product-centric MFA are summarized in Figure 17. The notations used to describe use phase and EOL are further explained in Table 19.

Table 19: Continuous and discrete notations of dissipative losses from use phase and end-of-life

Item	Notation (continuous)	Notation (discrete)
Total dissipative losses from use phase	$l_{Use}(t)$	$L_{Use}[n]$
- Losses from use phase to the environment.	$l_{Use,env}(t)$	$L_{Use,env}[n]$
- Losses from use phase to other material flows.	$l_{Use,omf}(t)$	$L_{Use,omf}[n]$
- Losses from use phase to landfills.	$l_{Use,lf}(t)$	$L_{Use,lf}[n]$
Recycled shares from EOL	$r_{EOL}(t)$	$R_{EOL}[n]$
Total dissipative losses from EOL	$l_{EOL}(t)$	$L_{EOL}[n]$
- Losses from EOL to the environment.	$l_{EOL,env}(t)$	$L_{EOL,env}[n]$
- Losses from EOL to other material flows.	$l_{EOL,omf}(t)$	$L_{EOL,omf}[n]$
- Losses from EOL to landfills.	$l_{EOL,lf}(t)$	$L_{EOL,lf}[n]$

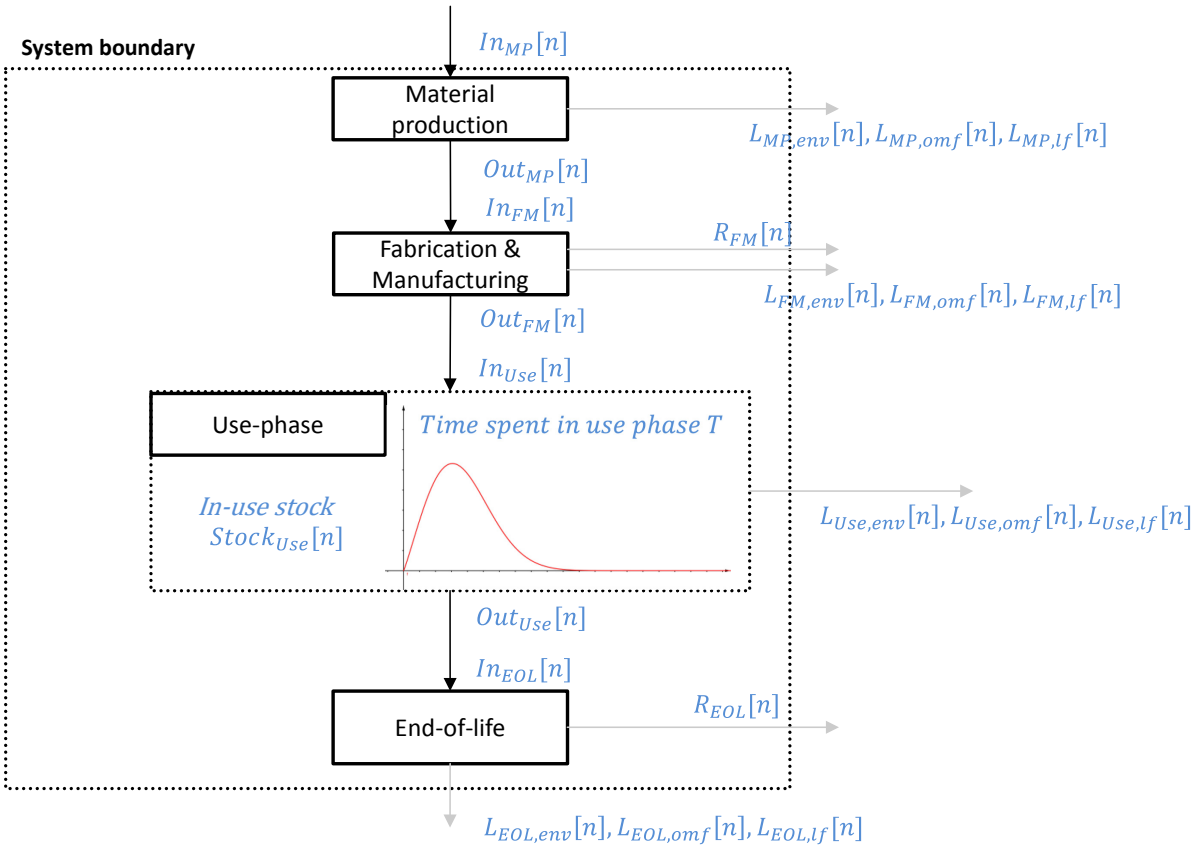


Figure 17: Main flows in approach for product-centric MFA

4.7 Data Requirements, Uncertainties and Scenarios

As described, the modeling approach is built around various parameters which determine the material flows along the product life cycle. Regarding the calculation of the model, “fixed flows” and “non-fixed flows” can be distinguished. In the model the inputs of the use phase are the fixed flows; all

upstream and downstream flows are non-fixed flows. The non-fixed flows are scaled according to the fixed flows with regard to the specific characteristics of the respective process stages (i.e., process efficiencies, recycling, and allocation of dissipative losses to receiving media).

The inputs to the use phase are calculated based on historic and future amounts of products placed on the market as well as metal concentrations in the products. Subsequently, the upstream material flows along material production, and fabrication and manufacturing are calculated based on efficiencies or loss rates, respectively; the downstream material flows, i.e., outputs from the use phase and material flows related to end-of-life, are calculated based on average lifespans and their distributions as well as the respective parameters describing the waste treatment at EOL.

The majority of these parameters are associated with uncertainties that need to be considered in the calculation. Generally, these uncertainties can be divided into two groups based on their influence on the modeling results. Besides uncertainties regarding parameters determining the relative dissipative losses (especially uncertainties regarding efficiencies or loss rates in the different life cycle stages), there are uncertainties determining the absolute material flows into use with corresponding changes in the upstream and downstream material flows. Regarding parameters mainly influencing the absolute material flows, a “min” and a “max” scenario are analyzed for the entire life cycle to show the range in which the absolute material flows might be located. As the main focus of the analysis is on the relative dissipative flows, uncertainties regarding the respective parameters are dealt with by considering different scenarios for each life cycle stage that represent the potential current situation and possible future developments. Combined with the min and max scenarios for the fixed flows, this results in a min and max “version” of each life cycle stage specific scenario. Whenever parameters are assumed to vary from 2012 to 2030, a linear progression of values is assumed if not otherwise indicated by available data.

Although uncertainties are rather product specific, there are some general remarks that can be made regarding the different life cycle stages. In material production and F&M such uncertainties arise from the existence of various process routes and missing knowledge about their shares and potential future development. In these cases, the focus is on the most relevant process routes, and assumptions regarding the future development are derived based on literature and/or expert judgments. This is particularly relevant for the stage of material production. Critical metals often occur in traces in the ores of other metals and in many cases are produced exclusively as by-products. Here, the scale of the losses significantly depends on the inclusion or exclusion of process routes, as critical metals are recovered in the processing of some ore while in the processing of other ores no recovery might be practiced. In such cases, the focus is on the processing of ores which are in fact treated for a recovery of the respective critical metals, while the processing of ores that contain the relevant critical metal but have so far not been subject of respective operations are analyzed in an additional scenario to highlight dissipative losses of critical metals which occur product-independently. Strictly speaking, the latter means an expansion of the system boundaries as defined at the beginning of

chapter 5 (material flows connected with analyzed products) but still provides valuable additional information regarding a more sustainable management of these metals.

Regarding the input flows to the use phase, the annual amount of products placed on the market as well as the metal concentration in the product are often associated with relatively large uncertainties. Regarding metal concentrations, often hardly any information is available from literature, and therefore manufacturers and/or other experts need to be consulted. Often, however, the respective information is not known to manufacturers/experts, and only ranges or estimations can be provided. Regarding the amount of products placed on the market, for some products at least historic data is available. Concerning the future development, published projections/forecasts are used which sometimes differ significantly from one another. This can lead to a rather large range between “min” and “max” flows into use. Regarding the time spent in the use phase (domestic service lifespan, see section 4.4) often only data on the average lifespans is available while information on the type of distribution and distribution parameters is scarce. In these cases, the Weibull distribution is chosen due to its flexibility and suitability to approximate other types of distribution and different shape parameters are analyzed in different scenarios.

For end-of-life treatment, there are principally three different options, recycling (including re-use of components, etc.), incineration, and landfilling. The classification of dissipative losses (determination of the receiving medium) is straightforward when EOL waste is landfilled. When EOL waste is incinerated, the residues (slag, ashes) might be landfilled but can be used as, e.g., filling or construction materials, which then corresponds to dissipation into other material flows. When critical metals are in fact recycled, the yield of the recycling process as well as the further fate of occurring losses (e.g., contaminant in other materials, i.e., losses to other material flows, or landfilling of, e.g., slags) needs to be regarded.

The uncertainties regarding the analysis of the case studies are described in detail in the respective sections. Table 20 summarizes the different flow types, data requirements, potential uncertainties, and how they are dealt with.

Table 20: Overview of flow types, data requirements and dealing with uncertainties

Flows type	Life cycle stage	Stocks/ flows	Data requirement with respective uncertainties	Dealing with uncertainties
Non-fixed	Material production	In_{MP}, Out_{MP}, L_{MP}	Process routes; shares; efficiencies; receiving media	Different life cycle stage specific scenarios
Non-fixed	F&M	In_{FM}, Out_{FM}, L_{FM}, R_{FM}	Process routes; shares; efficiencies; receiving media; treatment of production waste	Different life cycle stage specific scenarios
Fixed	Use phase	In_{Use}	Time series of products placed on the market; specific metal concentrations	Min and max scenario representing range of fixed flows
Fixed	Use phase	Out_{Use}, $Stock_{Use}$, L_{Use}	lifespans + distributions; in-use dissipation	Different life cycle stage specific scenarios
Non-fixed	EOL	In_{EOL}, Out_{EOL}, R_{EOL}, L_{EOL}	End-of-life treatment; recycling rates; receiving media	Different life cycle stage specific scenarios

5 CASE STUDIES: ANALYZING SELECTED PRODUCTS

In the following, in a dynamic product-centric MFA study, three products –copper-indium-gallium-(di)selenide (CIGS) photovoltaic cells (section 5.2), polymerization catalysts in the production of bottle grade PET (section 5.3), and thermal barrier coatings (TBC) used in aircraft engines (section 5.4)– are analyzed using the approach described in chapter 4. Material criticality, technology age, market dynamics, and scale of dissipative losses have been considered in the selection of the case studies, which is further motivated in the following.

With indium and gallium in CIGS photovoltaic cells, germanium in polymerization catalysts, and the heavy rare earth element yttrium in TBC, the selected products use metals that are commonly identified to be critical (see section 2.1), and show a high scale of dissipative losses (see section 3.1). In addition, this selection of products comprises technologies of different ages and degrees of establishment: With CIGS photovoltaic cells an upcoming technology with large growth rates is included; polymerization catalysts (in PET production) can be considered a well-established product, and TBC in aircraft engines are relatively well-established technology, but show a strong tendency to a further increased use to enable higher engine efficiencies. The latter results in carbon reductions (more coating allows higher operating temperatures and reduced fuel consumption) while on the other hand the demand for critical metals (in this case yttrium) is increased. Also for CIGS photovoltaic cells a similar trade-off can be observed as they are an integral part of most conversion strategies towards a low-carbon society but as well significantly increase the demand for indium and gallium.

The description of the case studies is structured following the main life cycle stages of material production, fabrication and manufacturing, use phase and end-of-life. The structure of the underlying models corresponds to the illustration provided in Figure 17, the further explanations in chapter 4, and the clarifications in the respective sections of chapter 5. For each of the main life cycle stages the relevant parameters as described in chapter 4 are identified, and descriptions on assumptions that have been necessary in the modeling process are given. In addition, the influence of uncertain parameters is looked at in a “min” and “max” scenario (see section 4.7) and selected additional scenarios in which parameters determining relative dissipative losses have been varied. Concluding the chapter, methodological constraints as well as limitations resulting from data availability are discussed in section 5.5. To start with, a short profile of the metals analyzed in the case studies is provided which includes general information on their production and demand situation as well as on their fields of application. This information underlines the selection of the case studies, provides details on the aspects influencing the materials’ criticality, and implies why dissipation should be reduced.

Scope definition

For the case study analysis, a timeframe of 2012 to 2030 has been chosen. For this time span, the cumulative dissipative losses (CDL) are determined in each case study for the different scenarios as

an aggregated indicator in addition to the detailed results (material flows including dissipative losses and stocks for each discrete time step, i.e., for each year). The CDL can be understood as the sum of dissipative losses into all considered media (environment, other material flows, and landfills) from 2012 to 2030.

Spatially, the analysis focuses on products used in Germany, i.e., only material flows connected with products used in Germany are considered. Other life cycle stages can, however, be located outside of Germany and are included in the study nonetheless. Cases in which the defined system boundaries have been expanded are noted explicitly.

Implementation

Calculations and visualization of material flows within the analyses of the case studies is carried out according to the methodological approach described in chapter 4 using Excel and the MFA software STAN 2.5, which has been developed by the TU Vienna, as well as the software eSankey for visualization through Sankey diagrams.

5.1 Metal Profiles

Although their relative abundance in the earth's crust is not particularly low, with indium being an exception (see Table 21), the metals of interest in the case studies have been identified to be critical in various criticality assessments (see section 2.1). This broad agreement on these metals' criticality is not least caused by their high and further growing importance as additives, catalysts, or dopants for semiconductors, etc., in various growing fields of application (see, e.g., Peiró, Méndez, and Ayres 2013) coupled with a high country and company concentration in production along other supply risks (Erdmann and Behrendt 2011; European Commission 2010), and partly a probably relatively low reserve base[45] (Erdmann and Behrendt 2011; European Commission 2010). Also for Germany, Erdmann and Behrendt (2011) identified their criticality to be high (indium, gallium, and rare earth elements) or even very high (germanium).

[45] The reserve base of a mineral is defined as the reserve (part of the resource which has been geologically evaluated and is commercially and legally mineable) plus those parts of resources that have a reasonable potential for becoming economically available within planning horizons. The correlation of reserve base and crustal abundance as well as deviations are discussed in (Mookherjee and Panigrahi 1994). As the reserve base considers the economic feasibility, it is, however, a very dynamic figure and particularly for indium, gallium, and germanium that are found in low concentrations in various ore of other metals and are mined as by-products, data on reserve bases is rather sketchy, inconsistent, and differs depending on the respective source (European Commission 2010; Graedel et al. 2011c; USGS 2014); e.g., the USGS does not provide any data on the reserve bases of germanium and gallium.

Table 21: Selected elements and their abundance (data compiled from Emsley 2011)

Element	Atomic number	Concentration in the earth's crust (ppm)	# most abundant element
Oxygen	8	470,000	1st
Silicon	14	280,000	2nd
Aluminum	13	82,000	3rd
Iron	26	41,000	4th
Zinc	30	75	24th
Copper	29	50	26th
Yttrium	39	30	28th
Gallium	31	18	34th
Lead	82	14	36th
Germanium	32	2	52nd
Silver	47	0.1	66th
Indium	49	0.1	69th
Gold	79	0.001	73rd

With their growing importance for various technologies, the production of the metals has increased rather steadily over the past decade. Figure 18 shows the production of refined material in the period 2000 to 2012.

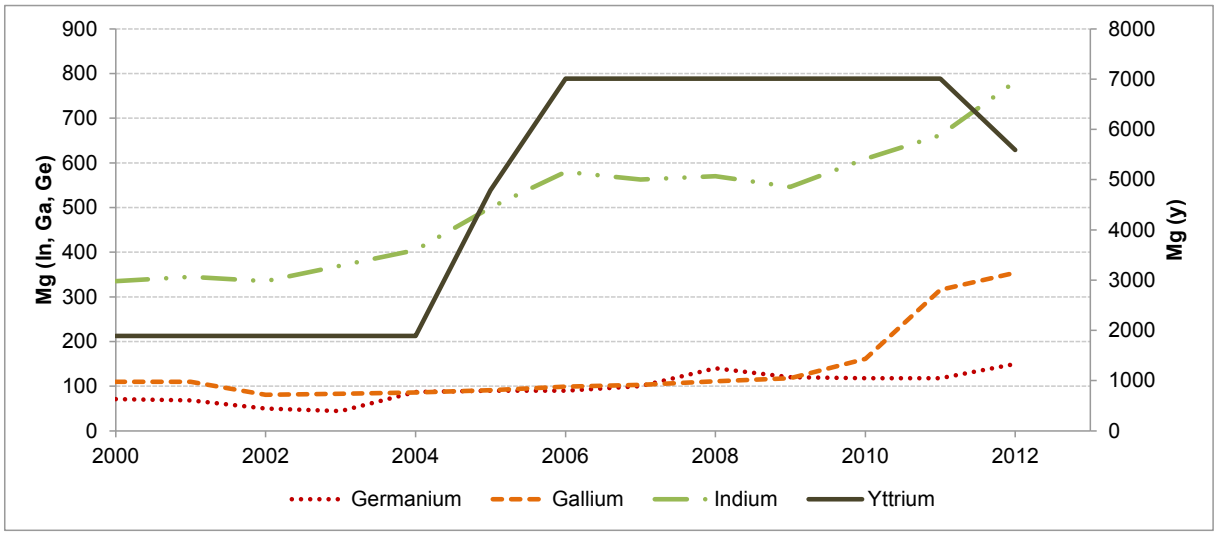


Figure 18: Refinery production of indium, gallium, germanium (left axis), and yttrium (right axis) (based on USGS data)

With this increase in production and the use in products which temporally remain in the technosphere, the stocks of these metals in the technosphere have been growing steadily just as have the dissipative losses of these materials since barely any recycling is practiced (cf. Graedel et al. 2011b). More details on the respective metals, their supply, demand and recycling situation are given in the following subsections.

5.1.1 INDIUM

Among the considered metals, indium is recognized to be the rarest with an average concentration in the earth's crust of 0.1 ppm (Emsley 2011). Its reserves (about 10,800 Mg) seem to be relatively well

studied, and a map of its major deposits can be found in (Reller et al. 2009). There are various indium minerals (see Table 22); however commercial production is almost exclusively limited to the production as a by-product within zinc production, due to a lack of economic incentives for a recovery from other sources.

The production and use of indium has increased by over 100 % in the past 10 to 12 years (cf. Figure 18). It has a major importance for different high-tech applications such as displays, LEDs, and photovoltaics. In these applications it is not easily substituted (Erdmann and Behrendt 2011). It is mainly used as indium tin oxide (ITO), but also in alloys and semiconductors.

Supply situation

Generally, indium deposits are widely spread. In ores, indium occurs exclusively in combination with other metals, mainly with zinc. Here, sphalerite is the most relevant mineral (Alfantazi and Moskalyk 2003). Various potential indium sources are summarized in Table 22. The biggest deposits of indium containing minerals can be found in China, Canada, Peru, the USA, Russia, Japan, and Portugal (Wittmer 2011; Reller et al. 2009). The biggest producer is China (over 50 % of world production), followed by the Republic of Korea, Japan, and Canada (USGS 2014). Also about 81 % of the imports into the EU originate in China (European Commission 2010). In 2012 the world refinery production of indium amounted to about 782 Mg while ten years before production was at 335 Mg (see Figure 18).

Table 22: Potential indium sources (data compiled from Schwarz-Schampera 2014; Alfantazi and Moskalyk 2003)

Source / Name	(Typical) indium content	Remark
Sphalerite	10-20 ppm	Main zinc ore; (Zn,Fe)S
Indium minerals		
Roquesite	47.35 wt.-%	$CuInS_2$
Laforetite	40.03 wt.-%	$AgInS_2$
Indite	55.50 wt.-%	$FeIn_2S_4$
Sakuraiite	24.35 wt.-%	$(Cu,Zn,Fe,Ag)_3(In,Sn)S_4$
Petrukite	6.05 wt.-%	$(Cu,Fe,Zn)_3(Sn,In)S_4$
Abramovite	11.41 wt.-%	$Pb_2SnInBiS_7$
Cadmoindite	49.58 wt.-%	$CdIn_2S_4$
Dzhalindite	69.23 wt.-%	In(OH)
Yanomamite	39.62 wt.-%	$InAsO_4 \cdot 2H_2O$
Yixunite	16.40 wt.-%	Pt_3In
Damiaoite	54.07 wt.-%	$PtIn_2$

Frequently, the production of indium as a by-product of other metals is described as a problem regarding the growing demand, as it is not economical to mine and produce indium alone, and a price increase for indium does not trigger an additional production of the carrying metals (e.g., Wittmer 2011). This is, however, not entirely true since the recovery of indium from zinc production still holds a lot of potential for improvement (see section 5.2.1), i.e., indium production could be further increased without additional mining and refining of the carrying metals.

Demand situation and applications

The current fields of application of indium are shown in Table 23. The main use of indium is as ITO in products in LCDs and with minor relevance in photovoltaic cells. ITO shows a good adherence to glass, transparency, and good electric conductivity. The next field of application –alloys and solders– includes a variety of different applications such as solders in electrical and electronic equipment (EEE), white gold alloys, dental alloys, control rods in nuclear power plants, bonding agents between nonmetallic materials (e.g., glass, glazed ceramics, quartz), auxiliary agents in optical industry, and fuses or plugs in sprinkler systems (Tolcin 2014; Tolcin 2012; Jorgenson and George 2004). Indium-containing solders have lower crack propagation and improved resistance to thermal fatigue when compared to tin-lead solders (Tolcin 2014). Melting points of indium alloys and solders range from 6.5 to 310°C (American Indium Corporation n.d.), qualifying it for a variety of applications.

Due to its abilities as a semiconductor, indium is used in LEDs and thin film photovoltaics such as CIGS cells. The use of indium as a semiconductor is so far only of little relevance, but significant future increases in demand are projected. For 2030, Angerer et al. (2009) expect a 285-fold increase of indium demand for PV compared to the 2006 demand (for LCDs a 7-fold increase is forecast, for LEDs a 15-fold increase).

Table 23: Applications of indium 2012/2013 (adapted from Zimmermann and Gößling-Reisemann 2014b with data from Tolcin 2014)

Application	Share
ITO (indium tin oxide), mainly used for LCDs, minor importance: thin-film PV	74-85 %
Alloys and solders	8 – 12 %
Semiconductor (LEDs, photovoltaics)	5 %
Other applications	2 -4 %

Recycling situation

The EOL recycling rate of indium from EOL products is below one percent (Graedel et al. 2011b). However, a recycled content (RC), i.e., a share of secondary (scrap) metal in the total metal input of metal production, of 25 % to 50 %, is reported (Graedel et al. 2011b), indicating a relatively well working recycling of production scrap. According to Niederschlag and Stelter (2009), the average recycling rate of production scrap is about 70 %.

5.1.2 GALLIUM

Gallium appears to be a particularly important element for Germany, with a share of 15 % to 25 % of the global consumption (Erdmann and Behrendt 2011) (corresponding to 53 to 89 Mg in 2012). Globally, production and use of gallium show a three- to fourfold increase from 2001/2002 to 2012 (USGS 2014). The main driver for this development has been the use in EEE.

Although gallium has a relatively high crustal abundance of 18 to 19 ppm (Emsley 2011; Butcher and Brown 2014) which is greater than of some metals considered to be significantly less critical (e.g., lead, tin), it is mainly found in minerals in trace quantities where it replaces other elements like alu-

minum (in bauxite) or zinc ores (in sphalerite). Although there are some minerals with a gallium content of up to 58 % (see Table 24), these are relatively rare and so far not suited for commercial mining (Butcher and Brown 2014).

Table 24: Potential gallium sources (data compiled from Butcher and Brown 2014; Cook et al. 2009; Moskalyk 2003; Greber 2000; Jolly and Heyl 1968)

Source / Name	(typical) Ga content	Remark
Bauxite	0.005 wt.-%	Ga content ranges from 0.003-0.008 wt.-%.
Sphalerite	0.015 wt.%	In some deposits significantly higher Ga content of 2.1-3.7 wt.-%.
Gallium minerals		
Gallite	35.3 wt.-%	$CuGaS_2$. Present in deposits in Namibia and DR Congo.
Sohngeite	57.7 wt.-%	$Ga(OH)_3$. Known deposit in Tsumeb, Namibia.
Gallobeudantite	14.6 wt.-%	$PbGa_3[(AsO_4),(SO_4)]_2(OH)_6$. Known deposit in Tsumeb, Namibia.
Carnevallite	20.9 wt.-%	Cu_3GaS_4. Known deposit in Tsumeb, Namibia.

Supply situation

So far, primary gallium is almost exclusively obtained as a by-product from the processing of bauxite. Principally there are other potential sources like zinc ores or fly ashes, but these are currently not exploited on a comparable scale (Elsner et al. 2010).

In 2013 the world primary production of gallium amounted to 280 Mg (metric tons) compared to 383 Mg in 2012. The biggest producers were China, Germany, Kazakhstan, and Ukraine (USGS 2014). As with indium, the production of gallium as a by-product is sometimes considered as a problem, as increases in demand cannot be flexibly responded to. However, there is still potential for optimizations of gallium recovery from bauxite processing (see section 5.2.2) as there are currently unused sources.

Demand situation and applications

As shown in Table 25, about two thirds of all gallium is used in EEE. Here, gallium is used in galliumarsenide wafers. Although so far about 90% of all wafers are silicon-based (Angerer et al. 2009), GaAs-wafers are ever more frequently used in high-performance applications such as smart and mobile phones, notebooks, and GPS navigation systems (Strategy Analytics 2012; Emsley 2011; Kammer 2011; Angerer et al. 2009) as they have operating speeds ten times higher than comparable silicon based wafers (Angerer et al. 2009). Besides EEE gallium is used in optoelectronic applications, mainly LEDs, and thin-film photovoltaics.

Future increases in demand are likely from galliumarsenide in mobile phones (Wittmer et al. 2011) or smartphones, respectively, LEDs, and thin-film photovoltaics (Erdmann and Behrendt 2011; Angerer et al. 2009).

Table 25: Applications of gallium in 2012/2013 (adapted from Zimmermann and Gößling-Reisemann 2014b with data from Jaskula 2014; USGS 2014)

Application	Share
EEE (microchips, integrated circuits)	61-68 %
Optoelectronic applications (LEDs, photovoltaic, photodetectors)	21 – 38 %
Other applications (Alloys, dental applications, …)	~1 %

Gallium can also be used to detect neutrinos emitted by the sun. For this purpose, in a project by Russian researchers, 50 Mg of gallium and more recently 100 Mg of gallium have been used by the Laboratori Nazionali del Gran Sasso (Emsley 2011) for the Gallium Neutrino Observatory in Gran Sasso, Italy. This led to significant shifts in the shares of the different applications of gallium shown in Table 25 in single years in the past.

Recycling situation

The EOL recycling rate of gallium is below one percent and the recycled content is between one and ten percent (Graedel et al. 2011b), indicating at least some recycling activities of production scrap. According to Wittmer (2011), recycling of production scrap is mainly carried out at bigger companies, while it is too expensive for small and medium enterprises.

5.1.3 GERMANIUM

As gallium, germanium is an element of particular importance for Germany with a share of the global consumption between 15 % and 25 % (Erdmann and Behrendt 2011) (corresponding to 22,500 kg to 37,500 kg in 2012). It is a crucial element for many high-tech applications such as glass fibers, photovoltaics, and infrared-sensors, but also for chemical-industrial processes like polymerization of high-grade PET.

There is a great variety of potential germanium sources. There are some rare germanium ores with germanium contents of up to 70 wt.-% like argyrodite and germanite, but none of those is mined commercially (Melcher and Buchholz 2014; Emsley 2011). Germanium is widely distributed in the ores of other metals, especially in zinc ores. Also some coal deposits contain significant concentrations of germanium and are used as a source (Emsley 2011; Melcher and Buchholz 2014). A collection of different potential germanium sources is given in Table 26.

Table 26: Potential germanium sources (data compiled from Roewer 2014 and Melcher and Buchholz 2014)

Source / Name	(typical) Ge content	Remark
Zinc sulphides (e.g., sphalerite and wurtzite)	up to 3,000 ppm	most relevant germanium source
Coal ashes		
E.g., coal ashes from Durham Coalfield, UK	1.1%	
Average content in ashes of Ge containing coals	30ppm to >1,000ppm	~30% of primary germanium production
Other zinc ores, e.g., willemite	up to 4,000 ppm	Zn_2SiO_4; minor zinc ore; rare
Copper sulfides (e.g., enargite, tennantine, bornite, chalcopyrite)	~ up to 100 ppm	
Other ores		
Cassiterite	up to 3,000 ppm	SnO_2; most important tin source; no germanium recovery
Hematite	up to 7,000 ppm	Fe_2O_3; important iron source; no germanium recovery
Goethite	up to 5,310 ppm	FeO(OH); minor important iron ore; no germanium recovery
Germanium minerals		
Argutite	70%	GeO_2
Argyrodite	5-7%	Ag_8GeS_6; first discovered Ge source
Canfieldite	1-2%	$Ag_8(Sn,Ge)(S,Te)_6$
Briantite	13-18%	$Cu_2(Fe,Zn)GeS_4$
Reniérite	4-8%	$(Cu,Zn)_{11}Fe_2(Ge,As)_2S_{16}$; relatively rare mineral
Germanite	5-9%	$Cu_{13}Fe_2Ge_2S_{16}$

Supply situation

Although a variety of potential sources exists, commercial germanium production is for the most part limited to the production as a by-product from zinc production and the recovery from coal ashes. The world refinery production of germanium was 155 Mg in 2013 and 150 Mg in 2012. The leading producer is China with a share of 70 % of the global germanium production, followed by Russia (USGS 2014). China is also the main supplier of germanium for Germany (Erdmann and Behrendt 2011).

Demand situation and applications

An overview of gallium applications is given in Table 27. The leading fields of application are fiber applications for telecommunication infrastructure followed by infrared applications and polymerization catalysts. As a semiconductor, germanium is used in EEE and photovoltaic cells. Although they have a significantly increased efficiency compared to silicon based solar cells (Elsner et al. 2010), the latter are so far mainly used in satellites and other space applications with an increasing relevance in the future. The main driver for future demand are, however, fiber cables followed by infrared-sensors (Angerer et al. 2009; Erdmann and Behrendt 2011).

Table 27: Applications of germanium in 2012/2013 (adpated from Zimmermann and Gößling-Reisemann 2014b with data from Roewer 2014; Guberman 2013; Höll, Kling, and Schroll 2007)

Application	Share
Optical materials – fiber applications	25-30%
Optical materials – infrared systems	25-30%
(Polymerization) catalysts	20-25%
Semiconductors (EEE, photovoltaics)	15-20%
Others (night vision, phosphors, medical applications; metallurgy)	15%

Recycling situation

Just like indium and gallium, EOL recycling rates for germanium are below one percent, the RC is however reported between 25 % and 50 % (Graedel et al. 2011b). Other sources report an RC of 30 % (European Commission 2010; Elsner et al. 2010) indicating a relatively well working recycling system for production scrap.

5.1.4 Rare Earth Elements

According to a definition of the IUPAC (International Union of Pure and Applied Chemistry), the rare earth elements (REE; also referred to as rare earths or rare earth metals) comprise the fifteen lanthanides (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium), as well as yttrium and scandium (Connelly et al. 2005). Occasionally, some authors do not classify scandium as a rare earth element (Jordens, Cheng, and Waters 2013). Even though their names indicate the contrary, they are in fact not really rare. The majority of the rare earth elements are situated in amounts larger than silver, between tin and lead, while the four most widespread elements (yttrium, lanthanum, cerium, and neodymium) are more abundant than lead (Kennedy 2014; Naumov 2008). Yttrium is the 28th most abundant element with an average concentration in the earth's crust of 30 ppm (Emsley 2011). The name "earths" was given to the REE at the end of the 18th century and was used at that time for refractory oxides insoluble in water (Naumov 2008).

Rare earths can be found in over 250 different minerals and some minerals contain up to 15 rare earth elements. So far, however, mainly three minerals are extracted on a commercial scale. These are bastnäsite, monazite, and xenotime (Kennedy 2014; Jordens, Cheng, and Waters 2013). Promethium does not have any stabile isotopes and cannot be found in nature. Scandium is produced as a by-product of uranium-extraction (Kennedy 2014).

The rare earths are often divided into two groups, light and heavy rare earth elements. The subgroup of light REE is sometimes also referred to as the cerium sub-group, lanthanide sub-group, or cerics, the heavy REE are also referred to as yttrium sub-group, or yttrics (Jordens, Cheng, and Waters 2013; Kingsnorth 2014; Naumov 2008). The light REE include lanthanum to europium (following the order of the periodic table), while the heavy REE include yttrium and the remaining lanthanides from gadolinium to lutetium. Less commonly, some authors add medium REE as a third sub-group

(e.g. Kingsnorth 2014; Kennedy 2014) (see Table 28). Scandium is commonly not included in either of the sub-groups and classifications, respectively (Jordens, Cheng, and Waters 2013; Kingsnorth 2014).

Table 28: Classifications of rare earth elements

Light rare earth elements	**Heavy rare earth elements**
Lanthanum, cerium, praseodymium, neodymium promethium, samarium, europium	Yttrium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium

Light rare earth elements	**Medium rare earth elements**	**Heavy rare earth elements**
Lanthanum, cerium, praseodymium, neodymium	Promethium, samarium, europium, gadolinium	Terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, yttrium

The rare earths are of increasing importance for a variety of high-tech applications, and imports to Germany are steadily increasing. Between 2004 and 2008 for example imports increased by 50 % (Erdmann and Behrendt 2011).

Supply situation

In total, rare earth oxide reserves amount to approximately one hundred million tons scattered over 30 countries (Jordens, Cheng, and Waters 2013). In the deposits, always several REE occur together in distributions that are hardly predictable (Gupta and Krishnamurthy 1992). Therefore, demand and supply situation of the different rare earth elements are usually difficult to match. If a demand for one rare earth metal exists, a market for the other mined REE has to be found (Kennedy 2014). So far, basically it has been the demand for REE for permanent magnets (Nd, Dy, Pr, Sm, Tb) that has acted as a main driver for the recent development of the rare earth industry (Kennedy 2014).

The main REE sources are the minerals bastnäsite, monazite, xenotime, and loparite as well as ion-adsorption clays. Bastnäsite and monazite are dominated –in terms of mass– by light rare earth elements (Kennedy 2014). Bastnäsite has a RE oxide (REO) content of between 70 and 75 % (mainly Ce and La; also Y), and monazite has a REO content of between 55 and 60 % (mainly Ce, La; also Nd, Y, and traces of other REE). Other relevant REE sources are (as said above) xenotime (REO content of 55 to 60 %, mainly Y, Eu, Gd), and loparite (REO content between 30 and 35 %, mainly Ce) (Kingsnorth 2014; Naumov 2008). Another important source for REE are ion-adsorption clays with a REO content of between 10 and 20 % (Naumov 2008). The latter are the main source for heavy rare earth metals, which are generally more valuable. Ion-adsorption clays mainly occur and are mainly mined in Southern China (Kingsnorth 2014; Kennedy 2014). Even though they are the most important source for heavy rare earth metals, it has to be noted that their composition and REO content may vary strongly (Kennedy 2014).Table 29 gives on overview on the main REE deposit, the respective minerals, and the respective REO share in relation to the total REO content. Quite generally, the supply of heavy REE is considered to be more critical than the supply of light REE due to their generally lower concentration in the deposits, the higher increase in demand from low carbon technologies among others, and the restrictive Chinese resource policy (Erdmann and Behrendt 2011). In addition, until recently

half of the supply of heavy REE came from illegal mining operations, against which serious actions are taken by the Chinese government since a couple of years (Elsner 2011).

Table 29: REO contents in major REE minerals (share in wt.-percent of total REO content) and deposits (data compiled from Kennedy 2014; Jordens, Cheng, and Waters 2013; Elsner 2011)

REO	Bastnäsite		Monazite				Loparite	Xenotime	Clays[46]	
	Bayan Obo, China	Mountain Pass, USA	Mt. Weld, Australia	Guandong, China	Steenkampskraal, South Africa	Green Cove Spring, USA	Lovozersky, Russia	Lehat, Malaysia	Xunwu, Jiangxi, China	Lognan, Jiangxi, China
La_2O_3	23.0	33.2-33.8	25.5	23.0	20.7	17.5	28.0	1.2	43.4	1.8
CeO_2	50.0	49.1-49.6	46.7	42.7	45.8	43.7	57.5	3.1	2.4	0.4
Pr_6O_{11}	6.2	4.1-4.3	5.3	4.1	5.1	5.0	3.8	0.5	7.1-9.0	0.7
Nd_2O_3	18.5	11.2-12.0	18.6	17.0	17.7	17.5	8.8	1.6	30.2-31.7	3.0
Eu_2O_3	0.2	0.1	0.6	0.1	0.1	0.2	0.1	traces	0.5	0.1
Tb_4O_7	0.1	traces	0.1	0.7	0.2	0.3	0.1	0.9	traces	1.0-1.3
Dy_2O_3	0.1	traces	0.2	0.8	1.0	0.9	0.1	8.3	traces	6.7-7.5
Y_2O_3	traces	0.1	0.4	2.4	4.2	2.5	traces	61.0	8.0	62.0-65.0
Sm_2O_3	0.8	0.9	-	-	-	4.9	-	1.1	3.9	2.8-5.0
Gd_2O_3	0.7	0.2	-	-	-	6.0	-	3.5	4.2	6.9
Ho_2O_3	traces	-	-	-	-	0.1	-	2.0	traces	1.6
Er_2O_3	traces	-	-	-	-	traces	-	6.4	traces	4.9
Yb_2O_3	traces	-	-	-	-	0.1	-	6.8	0.3	2.5
Tm_2O_3	traces	-	-	-	-	-	-	1.1	traces	0.7
Lu_2O_3	traces	traces	-	-	-	-	-	1.0	0.1	0.4

Until the late 1980ies, the U.S. were the dominant producer of REE, mainly due to the mining activities in Mountain Pass. Then, between 1990 and 2000, production of REE in China increased by over 450 % while production in other countries declined by over 60 percent (Tse 2011). Mountain pass, for example, closed operations in 2002, as did most other mines across the world. Reasons for this include high environmental impacts (wastewater, radioactive waste)[47] and respective legislations, making operations less economical. Thus the global share of REE produced in China increased to over 97 % for the years 2006 to 2010 and has been above 90 % ever since (USGS 2014). This concentration of rare earth productions was accompanied by a rather restrictive policy regarding rare earth exports and trade in China. In 1990, REE have been declared a protected and strategic mineral in China, which prohibits foreign investors from REE mining, smelting and separation projects except in joint

[46] Other deposits of REE containing clays are located in China in Guangdong, Fujian, Hunan, Yunnan and Guanxi. Of these, data on REO contents are only available for Guangdong (Elsner 2011): Y_2O_3: 20%, Sm_2O_4: 5.2%, Eu_2O_3: 0.7%, Tb_4O_7: 0.6%, Dy_2O_3: 3.6%.

[47] Rare earth mining and production is always connected with radioactivity and dealing with radioactive substances, respectively. Monazite deposits, for example, contain significant quantities of radioactive thorium, so do the bastnäsite deposits in Bayan Obo (Kennedy 2014). Ion-adsorbed clays as REE source are relatively lightly contaminated (Kennedy 2014).

ventures with Chinese firms (Tse 2011). In addition, public agencies issued production quotas as well as export quotas, the latter being gradually decreased until 2011 (Tse 2011). This led to a variety of new and re-opening mining projects across the world. Such projects can be found in the USA (namely Bear Lodge, Wyoming; Bokan Mountain, Alaska; Diamond Creek, Idaho; Elk Creek, Nebraska; La Paz, Arizona; Lemhi Pass, Idaho-Montana; Pea Ridge, Missouri; Round Top, Texas; and Thor, Nevada), Australia (Mount Weld), Brazil, Canada, Finland, Greenland, India, Kyrgyzstan, Madagascar, Malawi, Mozambique, South Africa, Sweden, Tanzania, Turkey, and Vietnam (USGS 2014). This development indicates that the rest of the world (the world besides China) has the potential to cover 90 % of the world demand for REE in the medium term (Kingsnorth 2014). However, the share of heavy REE in these newly exploited deposits is relatively low (Elsner 2011).

Demand situation / applications

REE have been used economically since approximately 50 years (Kennedy 2014). Especially in the past 15 years the demand increased significantly, resulting from a variety of new applications in which REE provide new or significantly improved functionalities. The main fields of applications for rare earth metals in 2012 have been permanent magnets (about 22 % of total REE production), alloys (about 20 % of total REE production), catalysts (industrial and automobile catalysts, about 19 % of total REE production), abrasives (about 13 % of total REE production), glass additives (about 8 % of total REE production), phosphors (about 7 % of total REE production), ceramics (about 6 % of total REE production) and others (5 %) (Kennedy 2014). The main fields of application and the relevant REE are presented in Table 30.

Table 30: Major driver for REE demand (adapted from Kingsnorth 2014; Kennedy 2014)

Application	Share in total REE demand	Rare earth elements	Main driver of demand
Magnets	~22 %	Nd, Pr, Sm, Tb, Dy	Hard discs, mobile phones, MP3-player, cameras, wind energy converter, motors, sensors, MRIs
LaNiH-Batteries	~20 %	La, Ce, Pr, Nd	Batteries for hybrid vehicles
Alloys		La, Ce, Pr, Nd	
Phosphors	~7 %	Eu, Y, Tb, La, Dy, Ce, Pr, Gd	LEDs, LCDs, phosphors
Catalysts for fluid catalytic cracking	~19 %	La, Ce, Pr, Nd	cracking processes in refinery industries – demand increases through rich oils and tar sands
Automobile catalysts		Ce, La, Nd	Demand increases through legislations regarding NO_x- and SO_2 emissions; platinum is recycled which is currently not economically for REE
Coatings	~6 %	Y	Coating in aircraft engines, gas turbines
Polishing powders	~13 %	Ce, La, Nd	Polishing of screens, mirrors, wafers
Abrasive ceramics		Y, Ce, La	Abrasives
Glass additives	~8 %	Ce, La, Nd, Er	Various applications
Glass fibers		Er, Y, Tb, Eu	Communication infrastructure

Future increases in demand are expected particularly from e-mobility, catalysis, miniaturized ICT, and wind energy (Erdmann and Behrendt 2011). For the near future (up to 2020) electric bikes and pedelecs have been identified to be the main driver in the demand for permanent magnet REE (Zimmermann and Gößling-Reisemann 2014b).

Recycling situation

Recycling of REE is as good as non-existent. EOL recycling rates of all REE are below one percent (Graedel et al. 2011b) and besides lab-scale research only few attempts to recycle EOL products have been made so far (Binnemans et al. 2013a). Data on the average recycled content (RC, fraction of secondary metal in the total metal input to metal production) however indicates that recycling of production scrap is at least practiced for some REE (lanthanum, cerium, praseodymium, neodymium, gadolinium, dysprosium are reported to have an RC of <10 %) while for the remaining REE the RC is below one percent, too (Graedel et al. 2011b). According to Du and Graedel (2011c) production scrap recycling is currently only conducted in magnet manufacturing.

Yttrium in particular

Yttrium is a heavy REE and thus considered to be particularly critical (e.g., European Commission 2014b; U.S. Department of Energy 2011; Elsner 2011). As for all REE, China is the leading producer of yttrium where it is produced from ion-adsorption clays mainly in the southern provinces of Fujian,

Guangdong and Jiangxi. Other countries (Brazil, India and Malaysia) account for less than 0.5 % (USGS 2014). Regarding the imports into the EU, the dominance of China is even bigger, supplying 99.9 % of all yttrium (European Commission 2014b). The global production of yttrium oxide amounted to about 7,100 Mg in 2012 and 2013 (USGS 2014).

The end-use of yttrium comprises: phosphors (flat panel televisions and displays, fluorescent lights; about 79 % in 2012), ceramics (ceramic applications, abrasives, bearings and seals, refractories, jet-engine coatings, wear-resistant and corrosion resistant cutting tools; about 21 % in 2012), and other uses (<1 %; metallurgy - grain refining additive, deoxidizer; heating-element alloys, high-temperature superconductor, the use of yttrium-iron garnets in microwave radar to control high-frequency signals and yttrium-aluminum-garnet laser crystals for dental and medical surgical procedures, digital communications, distance and temperature sensing, industrial cutting and welding, nonlinear optics, photochemistry, and photoluminescence) (European Commission 2014b; USGS 2014). As described before, yttrium is so far not recycled, neither from EOL products nor from production scrap.

5.2 CIGS PHOTOVOLTAICS

Among the analyzed case studies, CIGS PV cells[48] are –by far– the application that has received the most attention in science in the past years, mostly with regard to transitions of the energy system towards low-carbon energy generation and resulting material constraints (e.g., Stamp, Wäger, and Hellweg 2014; Zimmermann 2013a; Öhrlund 2012; Reiser, Rodrigues, and Rosa 2009) as well as upcoming challenges for recycling systems (e.g., Marwede et al. 2013; Marwede and Reller 2012; Berger et al. 2010). In fact, photovoltaic cells are a contributor to the global energy mix of rapidly growing importance. In 2010, approximately 15,000 MW of photovoltaic cells have been installed on a global basis (EPIA 2011), and average growth rates have been above 40 % in the decade 2000-2009 (Wolden et al. 2011). Further growth is expected for the future, in some scenarios even up to about 4,669 GW in 2050 (EPIA 2011).

On the technological side, so far there are basically two types to distinguish: silicon based cells and thin-film cells. Other types of PV cells like compound semiconductors[49] and nanotechnology cells are so far not yet relevant for commercial energy production (El Chaar, lamont, and El Zein 2011). In thin-film photovoltaic cells, the active layer has a thickness of between 1 and 10 µm which results in reduced manufacturing and material costs as well as an increased versatility. Efficiencies of thin-film cells are still lower than of crystalline cells, but costs, temperature robustness, and versatility led to a significant gain in market share over the past years (El Chaar, lamont, and El Zein 2011). A further growth is to be expected (e.g., Moss et al. 2011; U.S. Department of Energy 2011; European Commission 2010) resulting in increases in demand for certain metals such as indium, gallium, cadmium, and tellurium. These materials have been identified to be “critical” or “strategic” in various studies (e.g. indium and gallium in European Commission 2010; Buchert, Schüler, and Bleher 2009, tellurium in Moss et al. 2011; Thomason et al. 2010, and cadmium in Achzet et al. 2011). Some studies highlighted particularly their importance for energy technologies and low-carbon technologies or –the other way around– identified these materials to be a potential bottleneck for the expansion of renewable energies (e.g., Achzet et al. 2011; American Physical Society and Materials Research Society 2011; Buchert, Schüler, and Bleher 2009). With the continuous growth of installed photovoltaic capacity and a growing share of thin-film photovoltaic cells within the technology mix, a further increase in demand for these critical metals can be expected, while setting up a working recycling infrastructure that allows minimizing dissipative losses at EOL will be a major challenge.

[48] The CIGS case study is based on two previously published studies. In (Zimmermann and Gößling-Reisemann 2014a) material stocks and secondary material flows as well as the current recycling situation have been analyzed focusing on Germany. In (Zimmermann 2013a; Zimmermann 2013b) material flows, material demand, and material stocks resulting from photovoltaic deployment have been analyzed on a global basis.

[49] Compound semiconductor PV cells consist of a stack of crystalline layers with different band gaps which absorb most of the solar radiation, resulting in record efficiencies of over 40 %. Also referred to as heterojunction and multi-junction cells (El Chaar, lamont, and El Zein 2011).

5.2.1 Material Production Stage: Indium

Indium is exclusively produced as a by-product from the production of other metals. Mainly, indium is recovered from residues, fumes, dusts, fly-ashes, and slags of zinc production. Lead production, which is sometimes connected with zinc production, appears to be the second most important source for indium, while tin, antimony, and copper production are of minor importance (WVM 2013a; Alfantazi and Moskalyk 2003; Wittmer et al. 2011). The most common zinc containing mineral is sphalerite (ZnS) (Alfantazi and Moskalyk 2003). Besides indium, zinc ores usually contain other metals such as iron, lead, copper, cadmium, silver, gallium, and germanium (Lauwigi and Dressler 2011; Bräutigam et al. 2008; Initiative Zink 2013; Fthenakis, Wang, and Kim 2009; Classen et al. 2009).

Between 80 and 90 % of zinc are produced using hydrometallurgical processing (Bräutigam et al. 2008; Fthenakis, Wang, and Kim 2009). Pyrometallurgical processing that accounts for the balance is of minor importance. Among pyrometallurgical processes the Imperial-Smelting-Process is the only process still used in zinc production (Lauwigi and Dressler 2011; Bräutigam et al. 2008; Classen et al. 2009). The main stages of hydrometallurgical zinc processing and one possible route for indium recovery are shown in Figure 19.

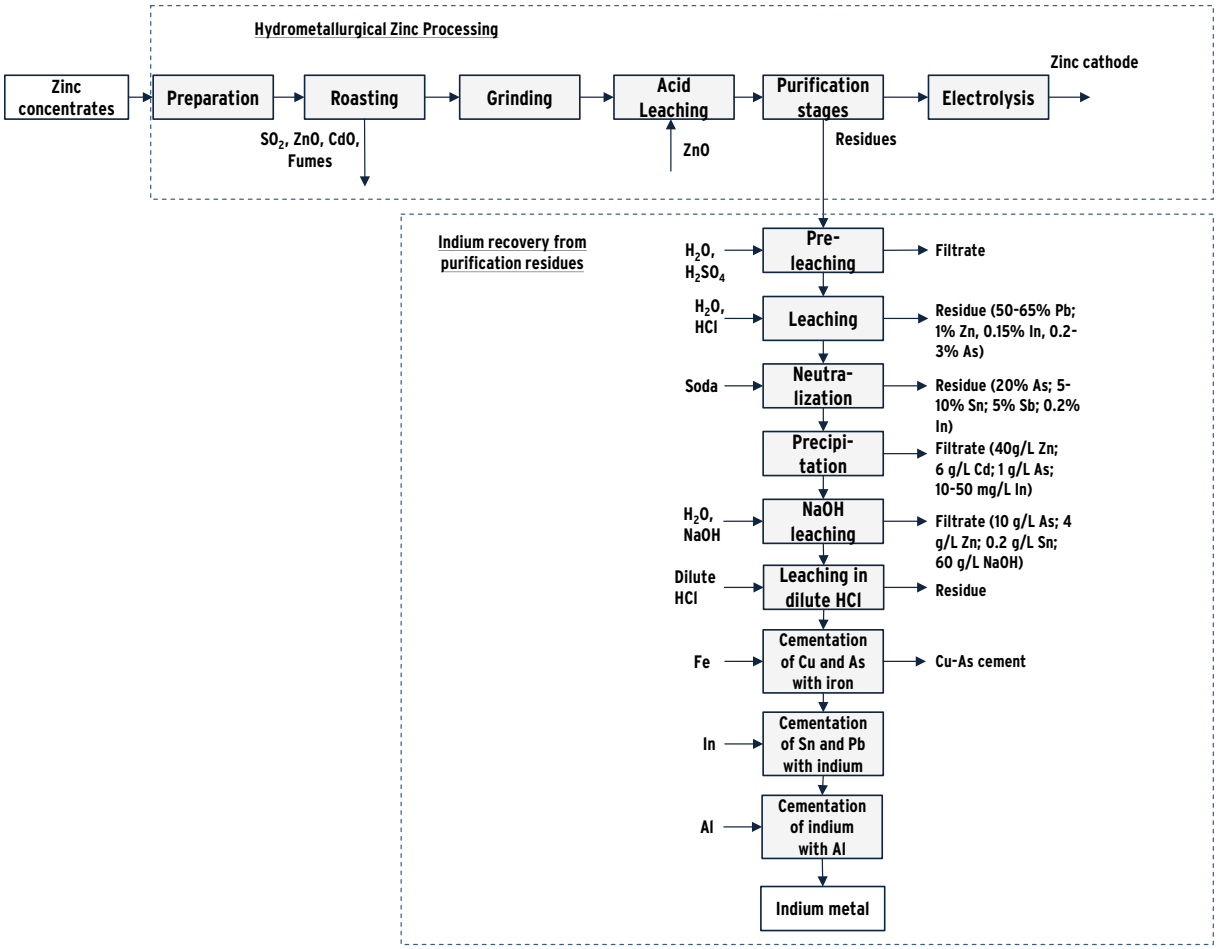


Figure 19: Hydrometallurgical zinc processing and indium recovery (zinc processing based on information from (Bräutigam et al. 2008; Fthenakis, Wang, and Kim 2009; Wittmer et al. 2011; Alfantazi and Moskalyk 2003); indium recovery process from (Fthenakis, Wang, and Kim 2009))

In zinc production, indium can be recovered from residues from roasting and purification stages. For recovery, different processes are applied such as the Harris process used by Umicore, the Waelz process, or the Jarosite process (see Alfantazi and Moskalyk 2003; Fthenakis, Wang, and Kim 2009; Wittmer et al. 2011 for further details on processes). The residues from zinc production are usually treated by acid leaching with subsequent electrolysis (Wittmer et al. 2011; Fthenakis, Wang, and Kim 2009).

For different process designs of indium recovery, recovery rates between 50 % and 80 % are reported. While recovery rates around 50 % seem to be an exception, recovery rates of 55 % to 65 % seem to be more representative for today's indium production (Wittmer et al. 2011; Alfantazi and Moskalyk 2003). Wittmer et al. (2011) estimate the indium losses in the material production stage to between 35 % and 45 %. Based on this range, two alternative scenarios –scenario A with 35 % losses in 2012 and scenario B with 45 % losses in 2012– are analyzed regarding the material production stage.

This range refers exclusively to such process routes which aim at a recovery of indium. There are, however, many process routes in which raw materials containing indium are processed without be-

ing recovered. As described in section 4.7, including these process routes in the analyses means an expansion of the defined system boundaries, as these process routes are not connected to the analyzed product. Still, valuable information about optimization potentials regarding the material production stage can be obtained. Not considered are, however, dissipative losses of indium contained in other ores such as the indium minerals given in Table 22. Here, data availability does not permit any estimate of dissipative losses.

Wittmer et al. (2011) and the European Commission (2010) estimate the share of indium contained in zinc ores ending up in processes unsuited for recovery to about 30 %. Studies considering the losses with regard to the indium contained in mined zinc ores, report losses of 70 % (Wittmer 2011) and 70 % to 75 % (Graedel, Gunn, and Tercero Espinoza 2014). The vast majority of these losses can be assumed to be landfilled (including indium containing dusts, ashes and residues that are not further processed) and only a minor share (<2 %) is assumed to dissipate to the environment (exhaust, flue gas etc.) or as a contaminant[50] to zinc and lead (based on Graedel, Gunn, and Tercero Espinoza 2014; Wittmer et al. 2011; Fthenakis, Wang, and Kim 2009; Bräutigam et al. 2008; Alfantazi and Moskalyk 2003). Based on this, an additional scenario (Scenario C) is analyzed. Here, for the base year 2012, total losses of indium from material production of 72 % are assumed, with 70 % to landfills, and 1 % each to the environment and other material flows.

Forecasts or projections on the future development of the recovery yield of indium in the material production have to the author's knowledge not been published so far. In a review study, Candelise, Speirs, and Gross (2011) emphasize the weak data availability and conclude that data availability and quality do not really allow any supply trajectories. Studies published regarding the future supply of indium do not include any information regarding assumptions made concerning the efficiency or yield of indium recovery from ore and concentrates.

In the past, besides the rather low yields of indium recovery processes, one of the main reasons for the high indium losses was that it was not economic to install the additional indium extraction capacity in existing zinc refineries (Graedel, Gunn, and Tercero Espinoza 2014). Due to increasing indium prices this situation is, however, likely to change in future. It is reported that smelters are improving the extraction process of indium, and raw material (concentrates) with lower indium content is more commonly processed. Increasing indium prices justify investments in research and development and equipment to increase indium recovery yields (Phipps, Mikolajczak, and Guckes 2008). Also, smelters able of indium recovery seek indium containing ores more actively than in the past when potential revenues did not justify a change of zinc concentrate suppliers and longer transport distances (Phipps, Mikolajczak, and Guckes 2008).

[50] Relevant publications, however, do not mention indium as a relevant contaminant since it is mainly contained in the residues from the leaching and purification stages (Roewer 2014; Fayram and Anderson 2008; Fthenakis, Wang, and Kim 2009); more relevant contaminants mentioned in literature are copper, nickel, cobalt, iron, and arsenic (Bräutigam et al. 2008).

Based on this and with regard to the lack of more accurate data, an improvement of the recovery efficiency by 10 % until 2030 is assumed for scenario A (increase of efficiency from 65 % to 71.5 %) and B (increase of efficiency from 55 % to 60.5 %). In scenario C the losses are assumed to remain constant. The assumptions for the different scenarios are summarized in Table 31.

Table 31: Indium losses from material production stage

		2012 A	2012 B	2012 C	2030 A	2030 B	2030 C
Dissipative losses	L_{MP}	35%	45%	72%	28.5%	39.5%	72%
- **to the environment**	$L_{MP,env}$	1%	1%	1%	0.5%	0.5%	1%
- **to other material flows**	$L_{MP,omf}$	1%	1%	1%	0.5%	0.5%	1%
- **to landfills**	$L_{MP,lf}$	33%	43%	70%	27.5%	38.5%	70%

Subsequent to the material production, further purification is required to obtain indium in a quality suited for photovoltaic applications. This purification is performed by vacuum distillation (Fthenakis, Wang, and Kim 2009). This step is reported to be free of losses (Wittmer 2011; Fthenakis, Wang, and Kim 2009) and is therefore not to be considered separately in the model.

5.2.2 Material Production Stage: Gallium

About 95 % of the global gallium production is obtained as a by-product of aluminum production from the processing of bauxite to alumina (Bayer process) (Fthenakis, Wang, and Kim 2009; Wittmer et al. 2011; Naumov 2013; Zhao et al. 2012). About 5 % are obtained from residues (slag) in zinc processing (Fthenakis, Wang, and Kim 2009), which appears to be less economical than recovery from alumina production (Wittmer et al. 2011).

In aluminum production, acid leaching and subsequent electrolysis are commonly used for gallium recovery (Fthenakis, Wang, and Kim 2009; Kausch and Matschullat 2005; Moskalyk 2003; Fayram and Anderson 2008), however, various different process designs are described in the literature (Zhao et al. 2012; Moskalyk 2003; Fayram and Anderson 2008). Often, hydrochloric acid is used to dissolve gallium and aluminum from metal hydroxides. Gallium is then separated by solvent extraction with ether producing a highly concentrated gallium residue still containing iron. Finally pure gallium is recovered by electrolysis (Fthenakis, Wang, and Kim 2009; Kausch and Matschullat 2005) (see Figure 20).

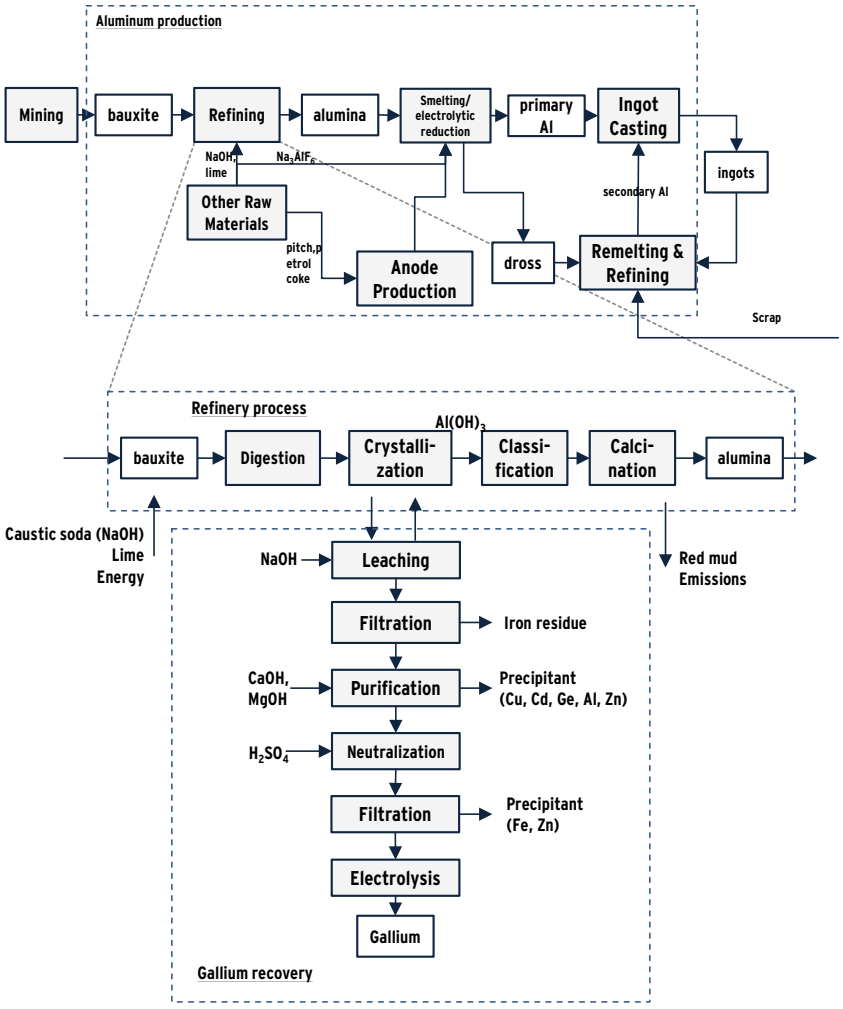


Figure 20: Simplified flow sheet of gallium recovery within aluminum production (based on information from EAA 2013; Liu and Müller 2012; Zhao et al. 2012; Ritthoff 2011; Leroy 2009; Fayram and Anderson 2008; Descriptions of alternative process routes can be found in Akcil et al. 2013; Zhao et al. 2012; Ritthoff 2011; Moskalyk 2003)

In general, information about gallium production is scarce (cf. Ritthoff 2011). In the production of gallium as a by-product in aluminum production, about 30 % of the contained gallium is reported to be disposed with the red mud (Akcil et al. 2013; Zhao et al. 2012), i.e. 70 % of the contained gallium are processed following the procedure described above. While most publications on gallium production do not report any further losses, Bautista (2003) reports recovery rates around 90 % (i.e., losses of around 10 %) for different process designs, and Akcil et al. (2013) report minor losses of gallium to electrofiltration dust without providing data allowing a quantification. Considering this, the total gallium losses in production as a by-product in aluminum production are estimated to about 37 % (scenario A) and can be assumed to be almost exclusively landfilled. In addition, slightly higher losses of about 45 % are assessed in scenario B.

Still, like in indium production, only a part of the gallium containing raw material (mainly bauxite) is treated in facilities that actually aim at a gallium recovery. Information quantifying the share of bauxite treated in respective facilities is hardly available, though. Greber (2000) reports that, in 1986, a complete utilization of gallium from aluminum oxide production would have corresponded to a gallium production of about 2,000 Mg. In fact, the 1986 world primary production of gallium is estimated

to about 35,000 kg or 35 Mg, respectively (Kramer 1988). I.e., in 1986, gallium losses from material production amounted to about 98.25 %. Of course, at that time there have been significantly less incentives for gallium recovery, and process technologies were much less developed. More recently, Phipps, Mikolajczak, and Guckes (2008) reported that less than 10 % of gallium potentially available from bauxite is actually extracted, referring to gallium losses from bauxite processing with and without gallium recovery corresponding to losses of about 90 %. An estimation can also be made based on the gallium content in bauxite and today's gallium and bauxite production. The average concentration of gallium in bauxite deposits is about 50 ppm[51] (USGS 2014; Elsner 2011), i.e. 0.005 wt.-%. This number is well in the range of gallium content in bauxite deposits of 0.003 to 0.008 wt.-% reported by Greber (2000) and Moskalyk (2003). Assuming an average gallium content of 0.005 wt.-%, a theoretical maximum production of 1,291 Mg (metric tons) of gallium in 2012 and 1,295 Mg in 2013 can be determined. Comparing this to the actual amount of gallium produced (383 Mg in 2012, 280 Mg in 2013) indicates gallium losses of 70 % to 78 % in the material production stage. Assuming gallium losses of about 37 % in the process routes for bauxite with gallium recovery, the share of bauxite treated in routes without gallium recovery can be estimated to be 66 % to 75 %. Based on this, in addition to scenario A and B, in scenario C the losses from process routes without gallium recovery are included, i.e., the system boundaries are expanded. Here losses of 78 % in 2012 are assumed. Analogous to indium production, other ores that potentially contain gallium (see Table 24) are not considered due to data availability.

The losses can be assumed to almost exclusively end up on landfills as being contained in red mud. Regarding the future development, in general, a similar situation as for indium is assumed, although –as for indium– hardly any information is available. Besides recovery yields, the main reason for the high gallium losses has been the lack of economic incentives to install additional recovery capacity in existing plants for bauxite processing, although the additional effort of recovering gallium from bauxite is described to be relatively low (Erdmann and Behrendt 2011). Assuming a growing demand for gallium from applications such as small EEE (mobile phones, smartphones, tablets, etc.), LEDs, and photovoltaics (cf. section 5.1.2), incentives are likely to be higher in the future. The respective assumptions are summarized in Table 32. Analogous to indium production, an improvement by 10 % until 2030 is assumed in scenario A and B.

[51] In contexts of geology, ppm is commonly understood as a measure of mass concentration or fraction, respectively, i.e. 1ppm=1mg/kg=0.0001 wt.-%. See for example (Perlman 2014). However, the IUPAC (International Union of Pure and Applied Chemistry) recommends not to use ppm but mol/mol or mg/kg to avoid confusions between molar and mass fractions (Schwartz and Warneck 1995).

Table 32: Gallium losses from material production stage

		2012 A	2012 B	2012 C	2030 A	2030 B	2030 C
Dissipative losses	L_{MP}	37%	45%	78%	30.7%	39.5%	78%
- **to the environment**	$L_{MP,env}$	1%	1%	1%	0.5%	0.5%	1%
- **to other material flows**	$L_{MP,omf}$	1%	1%	1%	0.5%	0.5%	1%
- **to landfills**	$L_{MP,lf}$	35%	43%	76%	29.7%	38.5%	76%

5.2.3 Fabrication and Manufacturing

The mass composition of photovoltaic modules is dominated by glass which accounts for about 80 % to 90 % of the total mass. About 10 % are made up by aluminum and copper or alternative materials. Critical materials in photovoltaic cells are located in the active layer and possibly in the transparent conducting oxide layer –see descriptions given below– and account for 0.1 % to 2 % of the total mass. Thus, only fabrication and manufacturing of the photovoltaic cell (as well as the downstream life cycle stages) are of interest in the following analysis, while other parts of the module like frames, inverters, or junction boxes are irrelevant regarding the analysis of indium and gallium flows.

The F&M of photovoltaic cells has seen an enormous geographic shift in the past decade. While Europe, Japan, and the U.S. have been the leading manufacturers of photovoltaic cells for years –accounting together for over 90 % of the globally produced modules in 2003 (Aratani 2005)– today, China is the leading manufacturer of photovoltaic cells. In 2013, seven out of the 10 leading companies producing photovoltaic cells were located in China (statista 2015b). The share of thin-film modules within the global production varied between 5.9 % and 16.8 % between 1999 and 2011 (statista 2015a). In Germany, however, a crisis of thin-film module manufacturer could be observed in 2011 and 2012, with several insolvencies, take-overs, and plant closures. This included companies like Solon, Q-Cells, First Solar, and Bosch Solar Energy (Wuppertal Institut 2014).

Cell manufacturing

Thin-film photovoltaic cells such as CIGS are produced by depositing thin layers of materials on glass or stainless steel substrates (El Chaar, lamont, and El Zein 2011). There is no standardized process for the deposition, and the applied methods can by categorized as vacuum methods and non-vacuum methods. Non-vacuum methods are of minor importance and can be further divided into electrodeposition, particulate deposition, and solution processes (Wolden et al. 2011). Vacuum methods –including methods like co-evaporation and selenisation– are the mostly used deposition approaches (Candelise, Winskel, and Gross 2012). The two-stage selenisation process which involves deposition of the metallic precursor on a substrate –often via sputtering– and selenisation of the layer in a second stage is, for example, applied by Solar Frontier, Miasole, and Avancis. The thermal co-evaporation process in which all elemental CIGS materials are vaporized and deposited onto the substrate in a vacuum environment is, for example, applied by Würth-Solar, Global Solar, and Ascent Solar (Candelise, Winskel, and Gross 2012).

Among the different processes, the co-evaporation process is described to currently be the best method with regard to costs, processing rates, reproducibility, and compositional uniformity (Marwede and Reller 2014).

Cell structure and material composition

The structure of CIGS photovoltaic cells consists of several layers between layers of glass. Molybdenum is deposited on the glass as a back contact followed by the CIGS absorber layer, a thinner CdS buffer layer, and layer of a transparent conducting oxide (TCO), often doped zinc oxide.

Table 33: Structure of CIGS photovoltaic cell (Bergesen et al. 2014; Marwede 2013; El Chaar, lamont, and El Zein 2011)

Glass	~4mm
Transparent conducting oxide	~1µm
CdS buffer layer (or InS)	0.05µm
CIGS (absorber)	1-2.5µm
Mo contact layer	0.5-1µm
Glass	~3mm

The CIGS layer is a mixture of copper-indium-di-selenide (CIS) and copper-gallium-di-selenide (CGS). Its chemical formula is $CuIn_xGa_{(1-x)}Se_2$. The x value can be between 0 and 1 reflecting different ratios of CIS to CGS (cf. Speirs et al. 2011). Thus, CIGS cells differ in their gallium content, but it can be said that modules without any gallium are rather uncommon (Sander et al. 2007). Current high-efficiency cells have a [Ga]/[In+Ga] ratio of 20 % to 30 % (Razykov et al. 2011; Romeo et al. 2004; N. Papathanasiou, pers. comm.).

The TCO can be composed of different materials. It is supposed to combine optical access (transparency) and a low-resistance electrical connection (conductivity). In addition, particularly for photovoltaic cells the choice of TCO material is driven by additional consideration such as material compatibility, processing, and costs (Fortunato et al. 2007). In the past, indium-tin-oxide (ITO) has been quite popular for use in photovoltaic cells, and there are prospective studies that assume an ongoing use of ITO in CIGS manufacturing for the coming decades (Wuppertal Institut 2014; Moss et al. 2011) resulting in a significantly increased indium demand. Since a couple of years, however, there has been a significant shift towards alternative material such as aluminum doped zinc oxide (Al:ZnO) and fluor doped tin oxide (F:SnO) which –according to expert information– can be assumed to have already replaced ITO completely in CIGS manufacturing (K.-H. Stegemann, pers. comm.). This is in accordance with studies explicitly dealing with TCO for photovoltaic cells which do not mention ITO as a relevant TCO in CIGS manufacturing and, instead, report Al:ZnO to be the main material for TCO in photovoltaics (Fortunato et al. 2007) or mention ITO only as one possible TCO among others (Klein et al. 2010). Particularly the steadily growing importance of Al:ZnO as an alternative to ITO with at least equal performance is frequently emphasized (Mereu et al. 2014; Szyszka et al. 2012; Fortunato et al. 2007; Romeo et al. 2004). Already in 2004, Romeo et al. (2004) mention that Al:ZnO is used more frequently as TCO than ITO.

Thus, it is assumed for the base scenario that neither ITO nor any TCO containing indium or gallium is used for TCO of CIGS photovoltaic cells.

Material utilization

The material efficiency in the two major processes –co-evaporation and selenisation via sputtering– is relatively well documented in different studies that serve as a basis for the modeling of the F&M stage. In co-evaporation, the source material is heated up under vacuum conditions until it evaporates and subsequently condensates onto a substrate (cf. Jung et al. 2010; Tanaka et al. 2006).

In sputtering, atoms are ejected from a solid target by bombardment with energetic particles, usually noble gases. Any substrate in the path of the ejected particles will be coated by a thin-film of the target material (cf. Shi et al. 2011; Sigmund 1987; Thompson 1981).

General data can be found in (Speirs et al. 2011). Here, the material efficiency in the various current CIGS cell production processes is described to range from 30 % to 50 %, while 75 % have been achieved in experimental processes (Speirs et al. 2011). Behrendt et al. (2010) and Zweibel (1999) report a process efficiency of about 50 %, which is in line with the data given by Chopra, Paulson, and Dutta (2004) who also mention a top efficiency of 75 % achieved in experimental processes.

Marwede and Reller (2014) provide process specific data for co-evaporation and sputtering processes (i.e., selenisation). In co-evaporation, efficiencies of 40 % to 55 % are described when using point sources and 50 % to 75 % when using linear vaporizers. In sputtering processes efficiencies of 30 % to 50 % are described for planar targets and 80 % for rotary targets (Marwede and Reller 2014). Similar efficiencies are reported by Woodhouse et al. (2012) with around 30 % for planar targets and 75 % for rotary targets as well as by Candelise, Winskel, and Gross (2012) with 33 % for planar targets and over 50 % for rotary targets. According to expert information, record material efficiencies of close to 100 % have already been achieved in processes in laboratory scale (M. Marwede, pers. comm.).

Based on this, it can be concluded that the current (base year) material efficiency in production ranges from 30 % to 80 %. Based on this, three scenarios, low-, mid-, and high efficiency are assessed in the study, representing efficiencies of 30 %, 55 %, and 80 %, with 55 % being assumed as the baseline case in the base year 2012. Regarding the future development, an increase of material efficiency to 67 % is assumed for the mid-efficiency (baseline) scenario as a combination of the assumptions made for 2030 by Zimmermann (2013a) (assumed efficiency of 60 % in 2030) and Stamp, Wäger, and Hellweg (2014) (assumed top efficiency of 73 % in 2030). For the high-efficiency scenario an increase to 90 % and for the low-efficiency to 35 % is assumed.

In addition to the material efficiency, the overall equipment efficiency needs to be considered which describes the share of cells rejected during production. These modules are directly discarded. Data on the overall equipment efficiency is given by Marwede and Reller (2014) and ranges from 80 % to 98 %. Here, again, three scenarios are used in the further analysis, representing efficiencies of 80 %,

89 %, and 98 % for the base year 2012. Regarding the future development, increases to 85 %, 95 %, and 99 % are assumed.

Based on both parameters, material efficiency and overall equipment efficiency, the material utilization in the F&M stage is determined to correspond to three different scenarios as shown in Table 34.

Table 34: Material efficiency, overall equipment efficiency, and material utilization in fabrication and manufacturing of CIGS photovoltaic cells

	Low efficiency		Mid efficiency		High efficiency	
	2012	**2030**	**2012**	**2030**	**2012**	**2030**
Material efficiency	30%	35%	55%	67%	80%	90%
Overall equipment efficiency	80%	85%	89%	95%	98%	99%
Material utilization	24%	29.75%	48.95%	63.65%	78.4%	89.1%
Production waste	76%	70.25%	51.05%	36.35%	21.6%	10.9%

Cell Efficiency

The cell efficiency describes the share of energy from solar irradiance that is converted into electrical energy. Information on the cell efficiencies is required to calculate the material intensity. Data on CIGS cell efficiencies from different sources is collected in Table 35.

Table 35: Current and forecast CIGS cell efficiencies

	Year / scenario					
(Fthenakis 2009)	**2008**	**2020, conservative**		**2020, most likely**		**2020 optimistic**
	11.2%	14%		15.9%		16.3%
(EPIA 2011)	**"Current" situation, low end**	**"Current" situation, top end**		**"Current" top lab efficiencies**		
	7%	12%		20%		
(Goetzberger, Luther, and Willeke 2002)	**Max lab efficiency in 2050**					
	26%					
(Bergesen et al. 2014)	**2010**	**2030**	**"long term efficiency potential"**			
	12%	20.8%	21%			
Expert information[52]	**2012 CIGS efficiency**					
	12.2%					
(Razykov et al. 2011)	**Global Solar Energy**	**Würth Solar**	**Shell Solar GmbH**	**Shell Solar Industries**	**Showa Shell**	
	10.2%	13%	13.1%	12.9%	13.4%	
(Marwede and Reller 2014)	**Average of nine manufacturers**					
	11.8%					
(Zuser and Rechberger 2011)	**2010, pessimistic**	**2010, optimistic**	**2020, pessimistic**	**2020, optimistic**	**2040, pessimistic**	**2040, optimistic**
	10.6%	10.6%	12.2%	15.0%	13.8%	19.4%

[52] Identity of expert cannot be disclosed, cf. (Zimmermann and Gößling-Reisemann 2014a).

Based on these data, a cell efficiency of about 12 % can be assumed for the base year. Regarding the future development, Bergesen et al. (2014) provide an estimation for 2030, assuming an increase to 20.8 %. This equals roughly the 2010/2011 top lab efficiency (EPIA 2011) and is close to a projection of the "most likely" 2020 scenario by Fthenakis (2009), assuming a linear increase to 2030. Zuser and Rechberger (2011) assume a much lower increase of efficiency to between 12.2 % and 15.0 % in 2030 and between 13.8 % and 19.4 % in 2040. Considering, however, that commercial modules already achieve cell efficiencies of 13.4 % (Razykov et al. 2011) and 20 % are already achieved in the lab, the assumptions by Zuser and Rechberger (2011) appear to be too conservative. Based on this, an efficiency of 20.8 % is considered a reasonable assumption for 2030.

Layer thickness

Data on the layer thickness and potential future development is collected in Table 36. The data varies from 1.0 µm to 2 µm for the current situation (comprising data published in 2009 and later). Also forecasts differ with a layer thickness of 0.8 µm to 1.2 µm forecast by Fthenakis (2009) for 2020, and 1 µm forecast by Bergesen et al. (2014) for 2030. The Zuser and Rechberger (2011) data and the Bergesen et al. (2014) data implicate a relatively high layer thicknesses for the timespan from 2012 to 2030. The origin of this data is, however, not entirely clear. For the Zuser and Rechberger (2011) data various older publications are referenced and the Bergesen et al. (2014) data is reported to be based on a non-published technical report by the U.S. National Renewable Energy Laboratories and a comparably old book article (Shafarman and Stolt 2003). Therefore, particularly the data provided by Marwede and Reller (2014) (which is based on expert consultations) and the information provided by Papathanasiou (N. Papathanasiou, pers. comm.) are considered more reliable. This leaves a range of 1.0 µm to 1.9 µm for the current situation and –based on (Fthenakis 2009) and information from (Marwede and Reller 2014)– a decrease to 0.8 µm to 1.2 µm by 2030.

Table 36: CIGS layer thickness

(Fthenakis 2009)	**2008**	**2020, conservative**	**2020, most likely**	**2020, optimistic**
	1.6µm	1.2µm	1.0µm	0.8µm
(Marwede and Reller 2014)	**Current situation, low end**	**Current situation, top end**	**Long term achievable**	
	1.0µm	1.9µm	0.8-1µm	
(N. Papathanasiou, pers. comm.)	**Current situation, low end**	**Current situation, top end**		
	1.3µm	1.5µm		
(Bergesen et al. 2014)	**Current situation**	**2030**		
	2µm	1µm		
(Zuser and Rechberger 2011)	**2010, pessimistic**	**2010, optimistic**	**2030[53], pessimistic**	**2030, optimistic**
	2	2	1.5	1.1

[53] 2030 data calculated based on estimations provided for 2020 and 2040 assuming a linear decrease.

Material intensity

There are various publications providing data of the material intensity of CIGS photovoltaic cells. These data refer partly to the amount per installed capacity, but also to the amount per cell area (e.g., in square meters). In these cases, a harmonization of the data was required. This has been done based on the efficiency of the respective cells η, the peak power output of the respective cell area W_p and the standardized assumptions of $\frac{W_{max}}{m^2}$=1000W/m² solar irradiance (Kuitche et al. 2012; Stollwerk 2001) using the following equation:

$$\eta = \frac{W_p}{m^2} \div \frac{W_{max}}{m^2} = \frac{W_p}{W_{max}}$$

Following this step of harmonization the data have been normalized to kg/MW for better comparability.

The data vary quite a bit and partly the data sources are untransparent. In addition, Moss et al. (2011) assumes an ITO-TCO which is not state of the art anymore, while other studies do not indicate the assumed type of TCO. Against this background, additional data from manufacturers and experts from research institutions are used. These data have partly previously been published (Zimmermann and Gößling-Reisemann 2014a; Zimmermann and Gößling-Reisemann 2014b; Zimmermann 2013a). As some of the manufacturers prefer not to have their identity disclosed, the entire expert and manufacturer data is presented anonymized[54]. Data on the material intensity from different publications and experts is given in Table 37.

Table 37: CIGS material intensity data from different publications

Study	Scenario	Indium [kg/MW]	Gallium [kg/MW]	Comment / [Ga]/[Ga+In] ratio	
(U.S. Department of Energy 2011)	"Low material intensity case"	15.4	12.4	No harmonization and normalization required.	44.6%
	"High material intensity case"	23.1	18.5		44.5%
(Moss et al. 2011)		18.99	2.34		11%
(Andersson 2000)		29	5.3	Data has been harmonized assuming a cell efficiency of 10%.	15.5%
(Stamp, Wäger, and Hellweg 2014)	2010/2030 optimistic	22.6/ 10.4	-	No harmonization and normalization required. No data on Ga content.	
	2010/2030 reference	27.5/ 14.6	-		
	2010/2030 pessimistic	38.6/ 25.4	-		
Expert/ manufacturer information A		15.9	12.8		44.6%
Expert/ manufacturer information B		24.4	19.7		44.7%
Expert/ manufacturer information C		18.3	14.7		44.5%
Expert/ manufacturer information D		9.8	3.8		27.9%

[54] Due to the limited number of CIGS cell manufacturers a partial disclosure of manufacturers would easily allow for an identification of the rest.

Regarding the data, particularly two aspects are noteworthy. The first aspect is the data range. The indium content varies from 9.8 to 24.4 kg/MW based on the expert data and from 15.4 to 38.6 kg/MW based on the literature data. The gallium data varies from 3.8 to 19.7 kg/MW based on the expert data and from 2.34 to 18.5 kg/MW based on the literature data. If the pessimistic scenario from Stamp, Wäger, and Hellweg (2014) which represents the very high end of the current situation (and only a slight improvement in the future), and the relatively old data from Andersson (2000) are not taken into account, the range of literature data for indium is slightly reduced to 15.4 to 27.5 kg/MW. The second aspect is the [Ga]/[Ga+In] ratio. While high-efficiency cells are reported to have a [Ga]/[Ga+In] ratio of between 20 % and 30 % (Razykov et al. 2011; Romeo et al. 2004; N. Papathanasiou, pers. comm.), the majority of the data indicates a ratio of close to 45 %.

It does not seem indicated to consider the entire data range in the model. As the data situation is relatively good, and at least parts of the data are based directly on expert information, and also the literature data can be assumed to be indirectly based on primary data, it would not make sense to analyze the low and top end of the data range, as the real mix will be located somewhat in between the top and low end of the data. Here, it has been decided to analyze a range from “mean minus standard deviation” to “mean plus standard deviation”. This means, for the base year 2012 a range of 14.4 to 24.7 kg/MW for indium, and 5.8 to 18.2 kg/MW for gallium are analyzed in the model.

Regarding the future development, technological improvements comprising reductions in layer thickness and increases in cell efficiency need to be taken into account. As described, an increase in cell efficiency from about 12 % in 2012 to 20.8 % in 2030 can be assumed. Layer thickness can be assumed to decrease from 1.0 to 1.9 µm in 2012 to 0.8 to 1.2 µm in 2030. This means, the increase in cell efficiency alone would decrease material intensity by a factor of up to 0.6; the decrease in layer thickness would decrease material intensity by a factor of up to 0.6. Together, this means a potential reduction of material intensity by a factor of roughly about 0.36. From the studies considered in Table 37, only Stamp, Wäger, and Hellweg (2014) provide an estimation on future reductions of material intensity. In their different scenarios they assume a reduction by a factor of between 0.46 and 0.66. Considering this, two scenarios –min and max– are analyzed in the model. In the max scenario a reduction of material intensity by a factor of 0.66 in 2030 compared to 2030 is assumed, in the min scenario a reduction by a factor of 0.36 is assumed. For the years before 2012 –starting from 1998– a linear decrease is assumed. The corresponding data is given for selected years in Table 38.

Table 38: Material intensity of CIGS cells pom [kg/MW]

	Indium		Gallium	
Year	**Min scenario**	**Max scenario**	**Min scenario**	**Max scenario**
1998	21.57	31.23	8.69	23.01
2012	14.40	24.70	5.80	18.20
2030	5.18	16.30	2.09	12.01

Recovery & treatment of production waste

Data on the recovery and treatment of production waste is relatively scarce and varies quite a bit. Wittmer (2011) indicates a recycling rate for production waste of about 70 %, Marwede and Reller (2014) assume a recycling rate of 50 %, noting, however, that there is a lack of available information on the recovery and treatment of overspray. Woodhouse et al. (2012) reports a recycling rate of 25 % which is considered to be "likely" by Marwede (2013). A similar recycling rate is given by Stamp, Wäger, and Hellweg (2014) with 27 % to 28 % for 2010. Stamp, Wäger, and Hellweg (2014) also provide assumptions regarding the future development of production waste recycling rates. In three different scenarios (pessimistic, reference, and optimistic), increases of the recycling rate to 51 % (pessimistic scenario), 62 % (reference scenario), and 76 % (optimistic scenario) are assumed. These scenarios are used in the model, assuming a linear increase from the 2010 values (27 % in both pessimistic and reference scenario, 28 % in optimistic scenario).

The non-recycled share of material can be assumed to be lost to slags or ashes depending on the used processes. Due to lack of information on the actual treatment of the production waste including the applied processes and treatment of residues, a 90/10 split of dissipative losses to other material flows and landfills, respectively, is assumed in accordance with the assumptions on the treatment of EOL waste (see section on CIGS cell end-of-life). The corresponding parameter settings are summarized in Table 39.

Table 39: Recycled share and dissipative losses in treatment of CIGS production waste

	Pessimistic		Reference		Optimistic	
Parameter	**2012**	**2030**	**2012**	**2030**	**2012**	**2030**
Recycled share	29.4%	51%	30.5%	62%	32.8%	76%
Dissipative losses	70.6%	49%	69.5%	38%	67.2%	24%
- **to other material flows**	63.5%	44.1%	62.6%	34.2%	60.5%	21.6%
- **to landfills**	7.1%	4.9%	7.0%	3.8%	6.7%	2.4%

5.2.4 USE PHASE

The most relevant parameter within the use phase is the number of annually installed CIGS photovoltaic cells. Based on these installations and the lifespan distribution of CIGS photovoltaic cells the flows into and out of use can be determined. As data for the annual installations is not directly available, the annual installations have to be determined based on the capacity development, the lifespan distribution and the share of CIGS solar cells within the technology mix.

Development of installed photovoltaic capacity

There is a variety of published studies with scenarios on future capacity development of renewable energies including photovoltaics. These scenarios differ quite significantly from each other, which results in significant changes regarding the material flows as demonstrated in (Zimmermann 2013a) on a global scale and in (Zimmermann and Gößling-Reisemann 2014b) for Germany, focusing on secondary material flows. In the following, the "low" and "high" scenarios used in (Wuppertal Institut

2014) are used as a basis for the calculations. These scenarios result from a review of various studies and cover the broad range of potential future developments described in nine different scenarios for the German market. The scenarios have been merged into a “low”, “mid”, and “high” scenario (Wuppertal Institut 2014). In those three scenarios historical data is used for the years before 2012, which is well in line with the scope of this study. As this thesis focuses on showing the potential range of absolute material flows, the “mid” scenario is not further considered in the following.

In the “low” (in the following referred to as “min”) scenario a linear increase of installed capacity from 25 GW in 2011 to 50 GW in 2050 has been assumed. The “high” (in the following referred to as “max”) scenario an increase of installed capacity to 100 GW in 2030 (and 120 GW in 2050) is assumed. These assumptions have been adapted slightly using historical data on PV installations from (BMWi 2014). According to the BMWi (2014) the installed capacity in 2011 amounted to 33,033 MW and in 2012 to 36,337 MW. I.e., in the min scenario an increase from 36,337 MW in 2012 to 42,809 MW in 2030 and in the max scenario to 100 GW in 2030 is assumed.

Share of CIGS cells in technology mix

While these numbers still refer to the installed capacity of all installed PV technologies, the share of CIGS cells within the technology mix needs to be considered, too. As described, there has been a serious crisis in the German thin-film market with a decline of the thin-film share in installations from 9 % in 2011 to 3 % in 2012 (Wuppertal Institut 2014). However, CIGS shares within the thin-film installations have almost doubled since 2010 increasing from 14 % in 2010 to 27 % in 2012 (Wuppertal Institut 2014). With regard to the total installations the share of CIGS cells amounted to 1.17 % in 2010, 1.32 % in 2011, and 0.75 % in 2012. For the years before 2010, country specific data has not been available. For the years 1999 to 2009 data on global shares of PV technologies from (PHOTON 2012) is used. Before 1999 CIGS cells have not been introduced to the market (N. Papathanasiou, pers. comm.). For the years after 2012, two scenarios provided in (Wuppertal Institut 2014) have been used. While there are other scenarios regarding the future shares of different thin-film technologies in PV installations (e.g., Moss et al. 2011; EPIA 2011), the scenarios provided in (Wuppertal Institut 2014) specifically refer to the situation in Germany and consider most recent events like the crisis in the German thin-film market.

The two scenarios regarding the future shares of CIGS cells within the technology mix used in (Wuppertal Institut 2014) are referred to as “continuity” and “thin-film renaissance”. In the “continuity” scenario no major changes on the PV market are assumed. Crystalline silicon cells will remain the dominant PV technology, while thin-film cells will remain a niche product with share of 2.04 % in 2020 and 1.36 % in 2030. Contrary, in the “thin-film renaissance” scenario a reversal of the trends of the past years is assumed, and CIGS shares increase to 7.92 % in 2020 and 15.33 % in 2030 (Wuppertal Institut 2014). For the years in between a linear development is assumed.

As the CIGS share refer to their share within the technology mix of new installations, the total annual photovoltaic installations need to be determined beforehand. For this endeavor knowledge on the lifespan distributions is required.

Lifespan and its distribution

As CIGS PV cells are a relatively young technology, empirical data on the service life span is rather scarce. Commonly, a lifespan of 20 to 30 years is assumed for photovoltaic cells without explicit differentiation of PV technologies (see, e.g., Wuppertal Institut 2014; Wolden et al. 2011; Azzopardi and Mutale 2010; Sherwani, Usmani, and Varun 2010; García-Valverde et al. 2009; Stoppato 2008; Briem et al. 2004). Most of these studies do not explicate their understanding of "lifespan"; however, implicitly most of them seem to mean the average lifespan –covering the timespan of installation until disposal (i.e., the average service lifespan). In the few studies dealing with actual lifespan observations of PV modules, average lifespans of 29.6 years (Kuitche 2010), 27.7, and 28 years (Kumar and Sarkan 2013) are reported. Some studies emphasize that thin-film modules have an average lifespan of more than 25 years (EPIA 2011; Berger et al. 2010), but no clear distinction between thin-film and crystalline silicon photovoltaic cells can be made. Against this background, average lifespans of 25 and 30 years are assumed in the min and max scenario, respectively.

Besides the average lifespan, knowledge on the lifespan distribution is required. Existing studies indicate that the Weibull distribution is the most adequate distribution to model lifespan distributions of photovoltaic modules and cells (see Kumar and Sarkan 2013; Kuitche 2010; Sharma, Rana, and Gupta 2010) and is therefore used in the model as well. In accordance with Zimmermann and Gößling-Reisemann (2014a) and Zimmermann (2013a) a shape parameter of k=5.3759 has been used as determined based on empirical data by Kuitche (2010).

Annual photovoltaic installations

The amount of annual installations results from the capacity development –particularly from increases in the capacity– as well as replacements of cells that have reached their EOL. Determining the increases in capacity is rather straightforward and can be done by simply subtracting the installed capacity in year *T* from the installed capacity in year *T+1*. The replacements of EOL cells are determined by applying the Weibull distribution to the installations starting from the base year 1990. Accordingly, the annual photovoltaic installations are determined.

Based on the annual photovoltaic installations and the two scenarios for the CIGS shares in the technology mix, a min and max scenario for the annual CIGS installations are developed. The corresponding installed capacity in selected years is shown in Table 40, the full data series are given in Appendix A) in Table A 1.

Table 40: Annual CIGS installations

	Min scenario [MW]	Max scenario [MW]
2012	24.79	24.90
2016	5.15	154.41
2020	8.38	290.81
2024	9.60	438.22
2030	14.79	830.26

Material flows into use phase

Following the methodological approach, a min scenario and a max scenario are defined varying the parameters that determine the absolute flows without changing the relative dissipative losses. As in this case study two critical metals –indium and gallium– are analyzed, for both a min and a max scenario is specified.

Table 41: Parameter settings in CIGS min and max scenario

	Indium		Gallium	
	Min scenario	**Max scenario**	**Min scenario**	**Max scenario**
Material intensity	As noted in Table 38			
Average lifespan	30 years	25 years	30 years	25 years
Annual CIGS installations	As noted in Table 40			

Based on these parameters, the material flows into use can be calculated for both scenarios and metals. The results are shown in Figure 21. For both metals, there is a huge difference between the min and max scenario, particularly from 2013 on. This difference results mainly from the scenarios on the PV capacity development and only to a lesser extent from the scenarios on material intensity and assumptions on average lifespans. As described, until 2012 the flows into use are based on real historic data on PV installations in Germany. From 2013 on, the min and max scenario from (Wuppertal Institut 2014) are used. The noticeable course of the graph –for both metals and scenarios– in the time span from 2007 to 2012 can be explained by the data on the CIGS shares within the total PV installations which are given in the appendix in Table A 1. After being relatively stable around between 0.2 % and 0.4 %, the CIGS shares quickly increase to 1.7 % in 2009, amount to about 1.2 % in 2010, increase to 1.3 % in 2011, and fall to 0.75 % in 2012. In the max scenario, the indium flows into use peak in 2009 at 3,274 kg and a steady increase from 2012 to 13,535 kg in 2030. In the min scenario, the indium flows peak in 2009 at 1,999 kg and decline steadily from 2012 on to 77 kg in 2030. The gallium flows into use look similar, however at lower absolute values due to the lower material intensity. In the max scenario they first peak in 2009 at 2,412 kg and steadily increase from 2012 on to 9,973 kg in 2030. In the min scenario they peak in 2009 at 805 kg and end in 2030 at 31 kg.

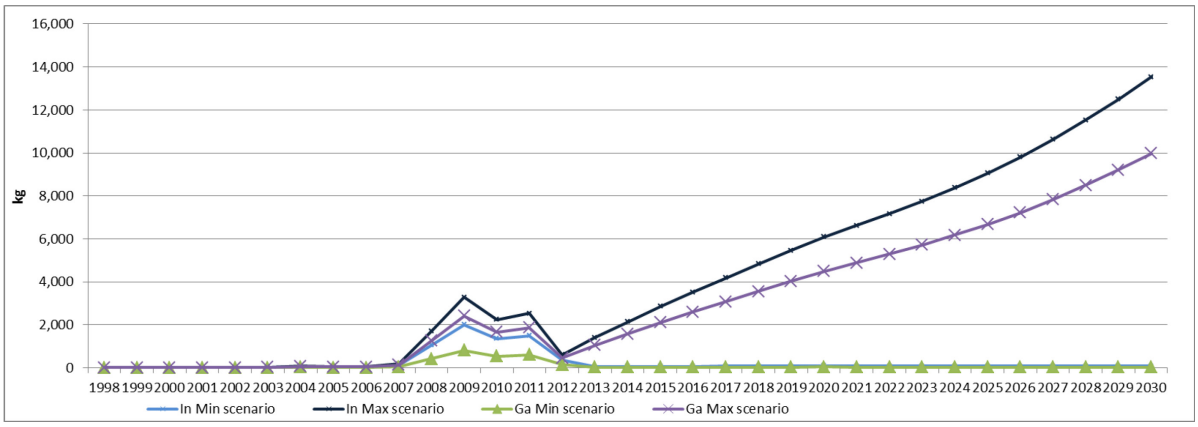


Figure 21: Indium and gallium flows into use

5.2.5 End-of-Life

CIGS photovoltaic cells can be considered a comparably "young" technology, particularly when considering the year of their first market entrance and their long service lifespan of over 25 years. Accordingly, only few CIGS cells have reached their end-of-life so far, and the existing commercially applied processes for dealing with discarded CIGS cells are almost exclusively limited to the treatment of production waste. However, there has been a lot of development regarding the collection of EOL modules, and various processes to recover critical metals from EOL CIGS cells are being currently developed.

Contrary to the other analyzed products –polymerization catalysts and thermal barrier coating– photovoltaic cells can be considered a business-to-consumer (B2C) product. This principally imposes some additional challenges for end-of-life, in particular by making the appropriate collection of EOL waste more challenging. This aspect is addressed by certain legislations on the EU and German level for electrical and electronic equipment (EEE).

On 14 August, 2013, the new WEEE (Waste Electrical and Electronic Equipment) EU directive (European Parliament 2012) became effective, which will be implemented in national law in Germany through an adaptation of the German ElektroG ("Elektro- und Elektronikgerätegesetz"). Currently, a draft bill for the implementation in Germany is available (BMU 2014), which can be expected to become law around mid-2015. The WEEE directive demands that manufacturers and importers of EEE ensure the collection and recycling of EEE fulfilling certain quotas.

The draft bill includes a reduction of the formerly ten categories for EEE to six groups. Photovoltaics are newly included in the law constituting a separate group (group 6: photovoltaics). From 2016 on, the mandatory collection quotas for WEEE in the draft bill are 45 % related to the average mass of products placed on the market (pom) in the past three years, which is a rather questionable approach regarding products with longer lifespans and high growth rates. From 2019 on, this quota will be increased to 65 % pom (BMU 2014). In the further EOL treatment, 75 % of the material need to be recovered and 65 % need to be recycled according to the draft bill and the WEEE directive, respectively.

Apart from that, it has to be noted that there are already different systems or schemes for the collection, taking-back, and recycling of photovoltaic modules, namely PV cycle, the E-Bell recycling system, the First Solar recycling system, and take-e-way (PV Cycle 2013b; Wambach and Wade 2013; Beckmann 2012; Landbell AG 2013). These systems have much more ambitious targets regarding the collection of PV modules and provide an infrastructure that makes a high collection rate of EOL PV modules likely –particularly compared to the law defined in the ElektroG.

Collection and recycling systems for EOL PV modules

Among the different collection and recycling systems, PV Cycle appears to be the most relevant one. PV Cycle was founded in 2007 by the European PV Industry as a non-profit association offering take-back, recycling, and waste management solutions for photovoltaic modules. PV Cycle is financed by the membership dues of manufacturers and importers and enables them to fulfil their legal obligations from the ElektroG and WEEE directive, respectively (PV Cycle 2013b). By PV Cycle's own account, they represent about 90 % of the European PV market and provide the only fully functional recycling scheme for all types of PV technologies in Europe. In Germany, they provide about 104 collection points, in Europe about 317 (PV Cycle 2013b). The disposal of EOL PV modules using PV Cycle's recycling scheme is free of charge for the modules' owners, and larger quantities (more than 40 modules) are collected upon consultation (PV Cycle 2013b). In 2012, about 3,759 metric tons of EOL modules have been collected by PV cycle, compared to 1,430 Mg in 2011 (PV Cycle 2013a). Among these, about 77 % have been crystalline silicon cells, 6 % amorphous silicon cells, and 16 % CIGS cells (PV Cycle 2013a).

The E-Bell recycling system has been founded by the Landbell AG in June 2013 for the take-back, disposal, and recycling of photovoltaic modules (Landbell AG 2013). So far, no dedicated collection points exist within the E-Bell recycling system, and collection and transport of EOL modules is organized individually.

First Solar is an associated member of PV Cycle and offers a collection and recycling system for their own modules (Beckmann 2012). The First Solar recycling system is prefunded and continues to operate after the shutdown of the First Solar plant in Frankfurt on the Oder (Wambach and Wade 2013). This system is, however, only relevant for CdTe cells.

Take-e-way provides solutions for manufacturers and importers of all kinds of EEE. For the renewed ElektroG coming into force in 2015, they also plan to provide solutions for the collection and recycling of photovoltaic modules (take-e-way 2014). Further details are, however, not yet available.

Collection quotas of EOL PV modules

Considering the respective legislations and the presence of working collection systems, a rather high collection quota for EOL PV modules can be assumed. Applying the ElektroG quota of 45 % and 65 % pom, respectively, to PV modules does not make much sense, particularly as PV modules are a rather young technology with high growth rates. Generally, considering the size of PV modules, their dis-

posal via the provided collection systems can be considered the norm, while differing disposal (e.g., via municipal waste) will be an exception. Against this background, the self-committed recycling quota by PV Cycle (as said above, representing 90 % of the PV market) of 85 % related to the arising EOL waste (PV Cycle 2012) seems more probable, at least as a conservative estimation. A collection rate of 85 % is also given as a conservative estimate for 2020 by other authors (Wambach 2013; Sinha, Cossette, and Ménard 2012). Thus, three different scenarios are analyzed in the model. In the low collection scenario a collection rate of 45 % in 2012 is assumed –based on the ElektroG quotas but referring to the arising waste– and an increase to 85 % in 2030. In the mid collection scenario a collection rate of 80 % in 2012, 85 % in 2020, and 95 % in 2030 is assumed. In the high collection rate scenario an increase from 85 % in 2012 to 98 % in 2030 is assumed. For the non-collected share, the treatment in non-dedicated waste management facilities without any indium or gallium recovery can be assumed. The indium and gallium content can then be assumed to be lost to slags or ashes that are used as filling or construction material or landfilled. Based on information from (ITAD 2014; Boh and Braga da Silva, Ledomiro 2014; Deike, Warnecke, and Vogell 2012; Faulstich et al. 2010) and in accordance with the assumptions explained below, a split of dissipative losses to other material flows of 90 %, and 10 % to landfills is assumed. Collection rates and resulting dissipative losses are summarized in Table 42.

Table 42: Scenarios for collection and dissipation of EOL CIGS modules

	Low collection			**Mid collection**			**High collection**		
	2012	**2020**	**2030**	**2012**	**2020**	**2030**	**2012**	**2020**	**2030**
Collected share	45%	65%	85%	80%	85%	95%	85%	95%	98%
Dissipative losses	55%	35%	15%	20%	15%	5%	15%	5%	2%
- **to other material flows**	49.5%	31.5%	13.5%	18%	13.5%	4.5%	13.5%	4.5%	1.8%
- **to landfills**	5.5%	3.5%	1.5%	2%	1.5%	0.5%	1.5%	0.5%	0.2%

Further treatment and processing of EOL PV modules

The collected EOL PV modules are further processed in respective facilities. According to the EU and German legislation, recovery rates of 75 % and recycling rates of 65 % apply. PV Cycle has even higher self-committed quotas of 80 % in 2015 and 85 % in 2020 (PV Cycle 2013b). Still, no recovery of semiconductor materials including indium and gallium, which account for about 0.1 to 2 % of the total mass, is conducted so far. As main reason for this lack of recycling of critical metals the still low amounts of EOL CIGS modules can be identified. Against the background of prospectively significantly rising EOL amounts, various processes for a recovery of critical metals from EOL PV cells are being developed. Companies involved in these developments are Loser Chemie (Palitzsch and Loser 2013; Palitzsch w/y), Solarcycle (Beckmann 2012), Lobbe (Lobbe 2012), and Saperatec (saperatec w/y). These processes have shown their feasibility in lab and partly pilot scale. As the main problem in the further development, the lack of thin-film waste is frequently emphasized. Further details on recycling processes for thin-film PV cells are given by Marwede et al. (2013), and Marwede (2013). The recovery efficiencies in these processes can be quantified to be between 70 % and about 95 %

(Marwede et al. 2013; M. Marwede, pers. comm.; T. Hübner, pers. comm.; Lobbe 2012). The actual application of these processes depends, however, on economy of scale, i.e., on the amount of EOL waste available for recycling as well as on future metal prices and legislation. Determining a threshold for the feasibility is beyond the scope of this study, though. Regarding the recycling of EOL CIGS modules, three different scenarios with constant recycling rates of 0 % (scenario "no recycling"), 70 % (scenario "low efficiency recycling"), and 95 % (scenario "high efficiency recycling") are analyzed in the model, showing different possible paths that depend on the use or disuse of available technologies.

Information on the fate of the non-recycled share is scarce and depends on the respective process design. In some processes the material can be assumed to end-up in the slag while in other processes –in chemical processes such as the Loser Chemie process– the material can be assumed to end up in wastes for incineration and finally in the incineration ashes. Both waste streams –ashes and slags– are commonly either used as construction or filling material or are landfilled. Studies dealing with the use and disposal of ashes and slags indicate that the use as construction or filling material is the much more common alternative (Wotruba and Weitkämper 2014; Weitkämper and Wotruba 2014; Boh and Braga da Silva, Ledomiro 2014; Dehoust et al. 2008). Different studies indicate a share of 90 % for use as construction or filling material –which corresponds to losses to other material flows– and 10 % for landfilling (ITAD 2014; Boh and Braga da Silva, Ledomiro 2014; Deike, Warnecke, and Vogell 2012; Faulstich et al. 2010). Based on this, for the non-recycled material 90 % dissipative losses to other material flows and 10 % to landfills are assumed. This allocation is assumed to remain constant until 2030. Although an increased recovery of metals from slags is ever more frequently discussed, indium or gallium recovery has not been a part of this discussion so far. The EOL parameters for the different scenarios for the end-of-life of CIGS cells are summarized in Table 43.

Table 43: Summarized EOL parameters for CIGS PV cells

EOL parameter	**Scenario & Year**								
Collection scenarios	**Low collection**			**Mid collection**			**High collection**		
	2012	**2020**	**2030**	**2012**	**2020**	**2030**	**2012**	**2020**	**2030**
Collected share	45%	65%	85%	80%	85%	95%	85%	95%	98%
Dissipative losses	55%	35%	15%	20%	15%	5%	15%	5%	2%
- to other material flows	49.5%	31.5%	13.5%	18%	13.5%	4.5%	13.5%	4.5%	1.8%
- to landfills	5.5%	3.5%	1.5%	2%	1.5%	0.5%	1.5%	0.5%	0.2%
	no recycling 2012-230			**low efficiency recycling 2012-2030**			**high efficiency recycling 2012-2030**		
Recycled share	0%			70%			95%		
Dissipation to OMF	90%			27%			4.5%		
Dissipation to landfills	10%			3%			0.5%		

5.2.6 *Results: Material Flows along the Life Cycle*

Using the different parameters for each life cycle stage as described above, various scenarios have been analyzed. Table 44 summarizes the parameter settings in the different scenarios structured according to the life cycle stages. For each scenario, a min scenario and a max scenario have been calculated following the explanations given in Table 41. The settings for the baseline scenario are indicated by shading of the respective cells in the table. Besides the baseline scenarios, major characteristics of the alternative scenarios are highlighted in the following, while the complete results for each scenario (min and max results) are given in Appendix A) in Table A 24 to Table A 46.

Table 44: Summary of analyzed scenarios along the life cycle of CIGS PV cells. Shading indicates the parameter setting of the baseline scenario.

Life cycle stage	Parameter	Scenario & Year		
Material production		**2012/ 2030 A**	**2012/ 2030 B**	**2012/ 2030 C**
Dissipative losses	$L_{MP,In}$	35% / 28.5%	45% / 39.5%	72% / 72%
	$L_{MP,Ga}$	37% / 31%	45% / 39.5%	78% / 78%
- to the environment	$L_{MP,env,In}$	1%/ 0.5%	1% / 0.5%	1% / 1%
	$L_{MP,env,Ga}$	1% / 0.5%	1% / 0.5%	1% / 1%
- to other material flows	$L_{MP,omf,In}$	1%/ 0.5%	1% / 0.5%	1% / 1%
	$L_{MP,omf,Ga}$	1% / 0.5%	1% / 0.5%	1% / 1%
- to landfills	$L_{MP,lf,In}$	33%/ 27.5%	43% / 38.5%	70% / 70%
	$L_{MP,lf,Ga}$	35% / 29.7%	43% / 38.5%	76% / 76%
Fabrication & manufacturing				
		2012 / 2030 low efficiency	**2012 / 2030 mid efficiency**	**2012 / 2030 high efficiency**
Material utilization		24% / 29.75%	48.95% / 63.65%	78.4% / 89.1%
Share of production waste		76% / 70.25%	51.05% / 36.35%	21.6% / 10.9%
Treatment of production waste		**2012 / 2030 pessimistic**	**2012 / 2030 reference**	**2012 / 2030 optimistic**
Recycled share	$R_{F\&M-II}$	29.4% / 49%	30.5% / 62%	32.8% / 76%
Dissipative losses	$d_{F\&M-II}$	70.6% / 49%	69.5% / 38%	67.2% / 24%
- to other material flows	$d_{F\&M-II,omf}$	63.5% / 44.1%	62.6% / 34.2%	60.5% / 21.6%
- to landfills	$d_{F\&M-II,lf}$	7.1% / 4.9%	7.0% / 3.8%	6.7% / 2.4%
Use phase				
Dissipative losses	d_{Use}	0%		
End-of-life				
EOL collection		**2012 / 2020 / 2030 Low collection**	**2012 / 2020 / 2030 Mid collection**	**2012 / 2020 / 2030 High collection**
Collected share		45% / 65% / 85%	80% / 85% / 95%	85% / 95% / 98%
Dissipative losses	d_{EOL-I}	55% / 35% / 15%	20% / 15% / 5%	15% / 5% / 2%
- to other material flows	$d_{EOL-I,omf}$	49.5% / 31.5% / 13.5%	18% / 13.5% / 4.5%	13.5% / 4.5% / 1.8%
- to landfills	$d_{EOL-I,lf}$	5.5% / 3.5% / 1.5%	2% / 1.5% / 0.5%	1.5% / 0.5% / 0.2%
EOL Recycling		**2012 / 2030 no recycling**	**2012 / 2030 low efficiency recycling**	**2012 / 2030 high efficiency recycling**
Recycled share	R_{EOL-II}	0%	70%	95%
Dissipative losses	d_{EOL-II}	100%	30%	5%
- to other material flows	$d_{EOL-II,omf}$	90%	27%	4.5%
- to landfills	$d_{EOL-II,lf}$	10%	3%	0.5%

Baseline scenario

Figure 22 visualizes the material flows for selected years (2012, 2013, 2021, and 2030) for the baseline scenario. In the baseline scenario as well as in the other scenario, a huge difference regarding all flows in the analyzed system between min and max scenario is obvious, which results from the underlying PV expansion scenarios. Evidently, assuming higher PV installations results in increased material flows and vice versa. As the installations in 2012 are based on real life data, while from 2013 on

scenarios have been used, there is a significant difference between the size of the material flows in 2012 and 2013 in the min scenario in which a much more moderate growth is assumed compared to the max scenario. E.g., in 2012 the indium demand (input to F&M) amounts to 729 kg, while in 2013 it amounts to 92 kg. Therefore, the following discussion of results focuses on the period from 2013 to 2030 which better emphasizes long term trends.

Throughout the considered period in time, dissipation appears to be the major fate of material leaving the system. In 2012/2013 about 88 % of the total outputs are dissipative losses while about 12 % are secondary material flows –mainly from fabrication and manufacturing (F&M). Until 2030 the share of dissipative losses in relation to the total outputs decreases to about 56 % in the min scenario and 76 % in the max scenario. The material mainly dissipates to landfills. In the min scenario, the share of dissipative losses to landfills decreases from 70 % for indium and 67 % for gallium in 2013 to 61 % for both, indium and gallium in 2030. In the max scenario, the share of dissipative losses to landfills increases from around 70 % to 81 % for both metals. For both, min and max scenario, dissipation to the environment can be considered negligible. Dissipation to other material flows increases in the min scenario as dissipation to landfills decreases, while its share decreases from about 28 % to 18 % in the max scenario.

The material production (MP) stage appears to be the major hot spot regarding dissipative losses. In the min scenario, the relative share of dissipative losses from material production in relation to total annual dissipation decreases from 70 % in 2013 (corresponding to about 74 kg of indium and 30 kg of gallium) to 58 % in 2030 (corresponding to about 78 kg of indium and 32 kg of gallium), while the absolute amounts increase. In the max scenario, the relative share of dissipative losses from MP increases from about 70 % in 2013 (corresponding to about 2,295 kg of indium and 1,691 kg of gallium) to 81 % in 2030 (corresponding to about 13,883 kg of indium and 10,230 kg of gallium).

Besides MP, dissipation occurs at F&M and EOL from not recycled wastes. In the min scenario, dissipation from F&M accounts to about 30 % of the total dissipation in 2013 which decreases to 12 % in 2030. In the same time span, the share of dissipation from EOL in relation to the total annual dissipation increases from 0 % in 2013 (corresponding to about 15 kg of indium and 6 kg of gallium) to 30 % in 2030 (corresponding to about 109 kg of indium and 44 kg of gallium). In the max scenario, the share of dissipation from F&M decreases from about 30 % in 2013 to 17 % in 2030. Dissipation from EOL is, in relative terms, negligible with a share of 0 % in 2013 and 1 % in 2030. In absolute terms, however, the annual amount of recycled material grows from 460 kg of indium and 339 kg of gallium in 2013 to 5,251 kg of indium and 3,869 kg of gallium in 2030.

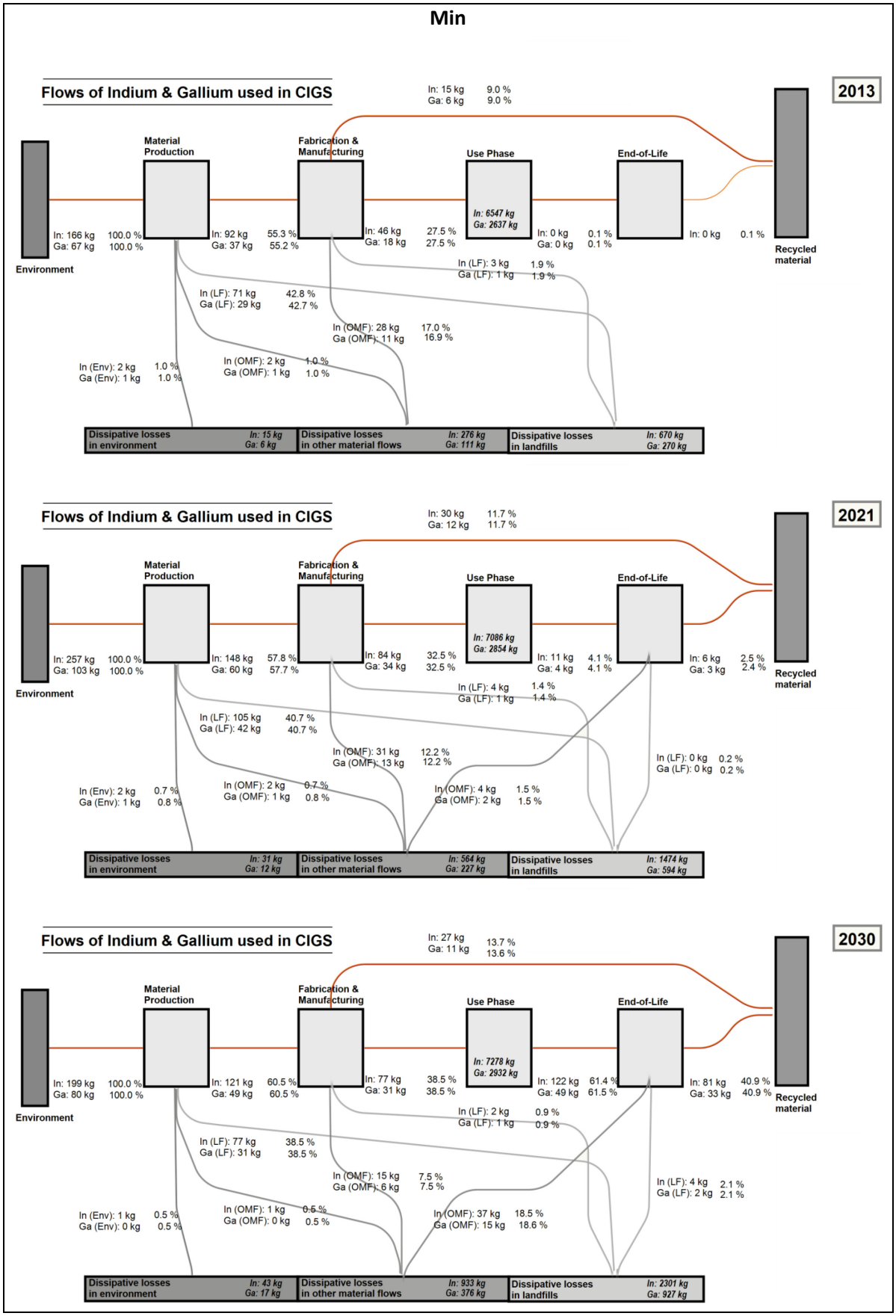


Figure 22: Indium and gallium flows in CIGS baseline scenario; relative flows refer to input flow from environment (input to material production = 100%); percentages may not add up to 100% due to rounding differences.

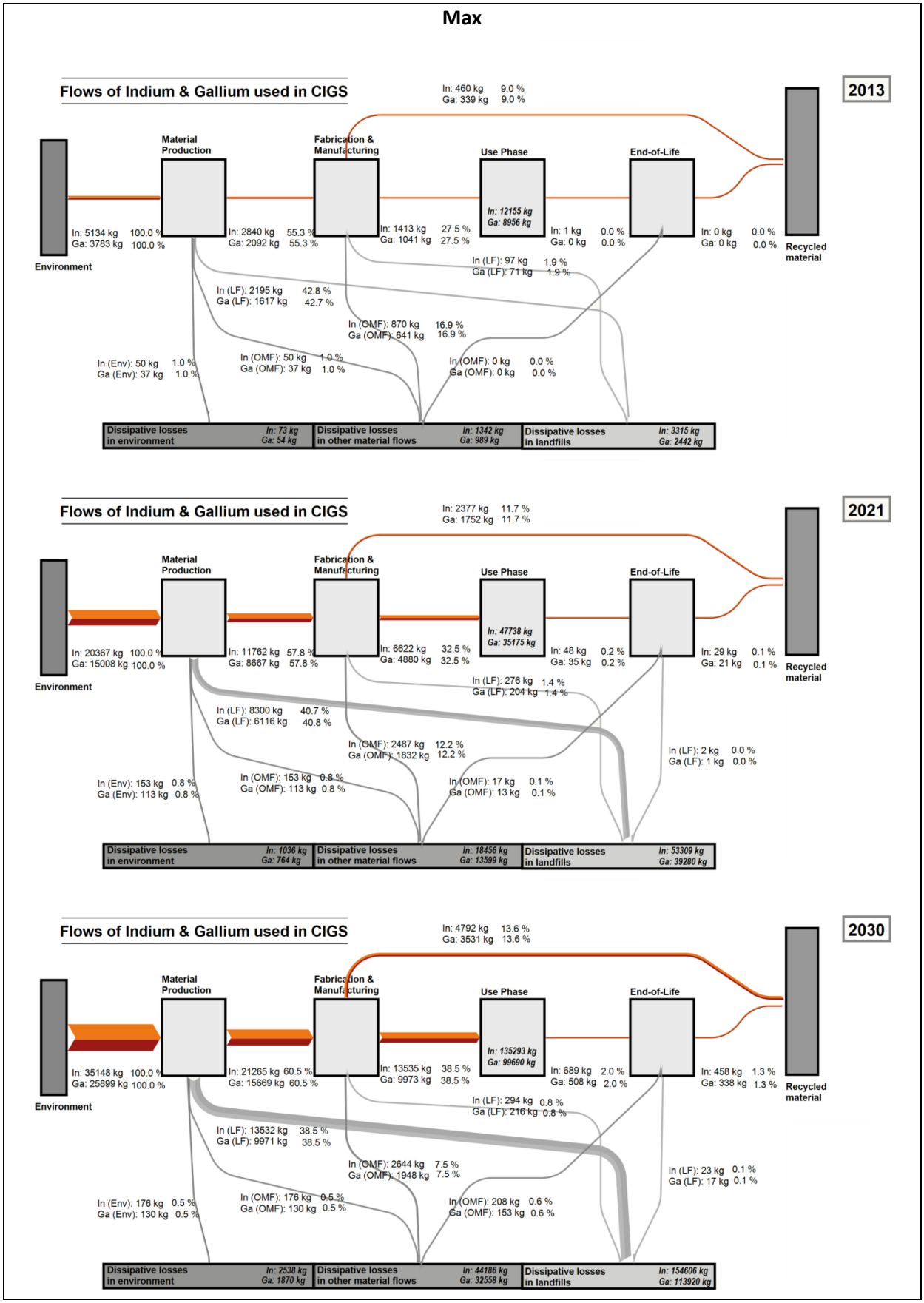


Figure 22 continued.

Regarding indium demand (i.e., input to F&M) there is a factor of 31 between the baseline min and max scenario in 2013, which increases to 176 in 2030. Regarding gallium demand the difference is even bigger and increases from a factor of 56 in 2013 to 323 in 2030. In terms of absolute flows this means an increase of material demand from 92 kg to 2,840 kg of indium in 2013 to 121 kg to 21,265 kg indium in 2030. For gallium, material demand increases from 37 kg to 2,092 kg in 2013 to 49 kg to 15,669 kg in 2030. In the same time span, EOL secondary material flows (output from use phase/ input to EOL phase) of indium increase from 0.13 kg to 0.5 kg in 2013 to 122 kg to 689 kg in 2030. Secondary flows of gallium increase from 0.1 kg to 0.4 kg in 2013 to 49 kg to 508 kg in 2030. In the min scenario, in 2030 the EOL secondary material flows even exceed the material demand.

The in-use material stocks grow from 6,501 kg of indium and 2,619 kg of gallium in 2012 in the min scenario to 7,278 kg of indium and 2,932 kg of gallium in 2030. In the max scenario, the indium stocks increase from 10,743 kg in 2012 to 135,293 kg in 2030. The gallium stocks increase from 7,916 kg in 2012 to 99,690 kg in 2030.

Material production scenarios

As described, the material production stage appears to be a major hot spot in terms of dissipative losses. Besides the material production scenario considered in the baseline scenario (MP scenario B), two alternative scenarios have been assessed.

In MP scenario A, somewhat lower losses than in MP scenario B have been assumed. Compared to the baseline scenario, cumulative dissipative losses (CDL) are reduced by 21 % to 29 % throughout the considered time frame. This clearly shows how dissipation can be reduced through an optimization of the MP stage. The material flows of MP scenario A are shown in Figure 23.

In MP scenario C, the system boundaries have been expanded including dissipative losses not strictly related to the life cycle of CIGS PV cells but to indium and gallium contained in mined ores. This results in significantly increased dissipative losses. CDL of indium are increased by 170 % in the min scenario and 203 % in the max scenario. CDL of gallium are increased by 261 % in the min scenario and 308 % in the max scenario. Figure 24 visualizes the material flows of MP scenario C.

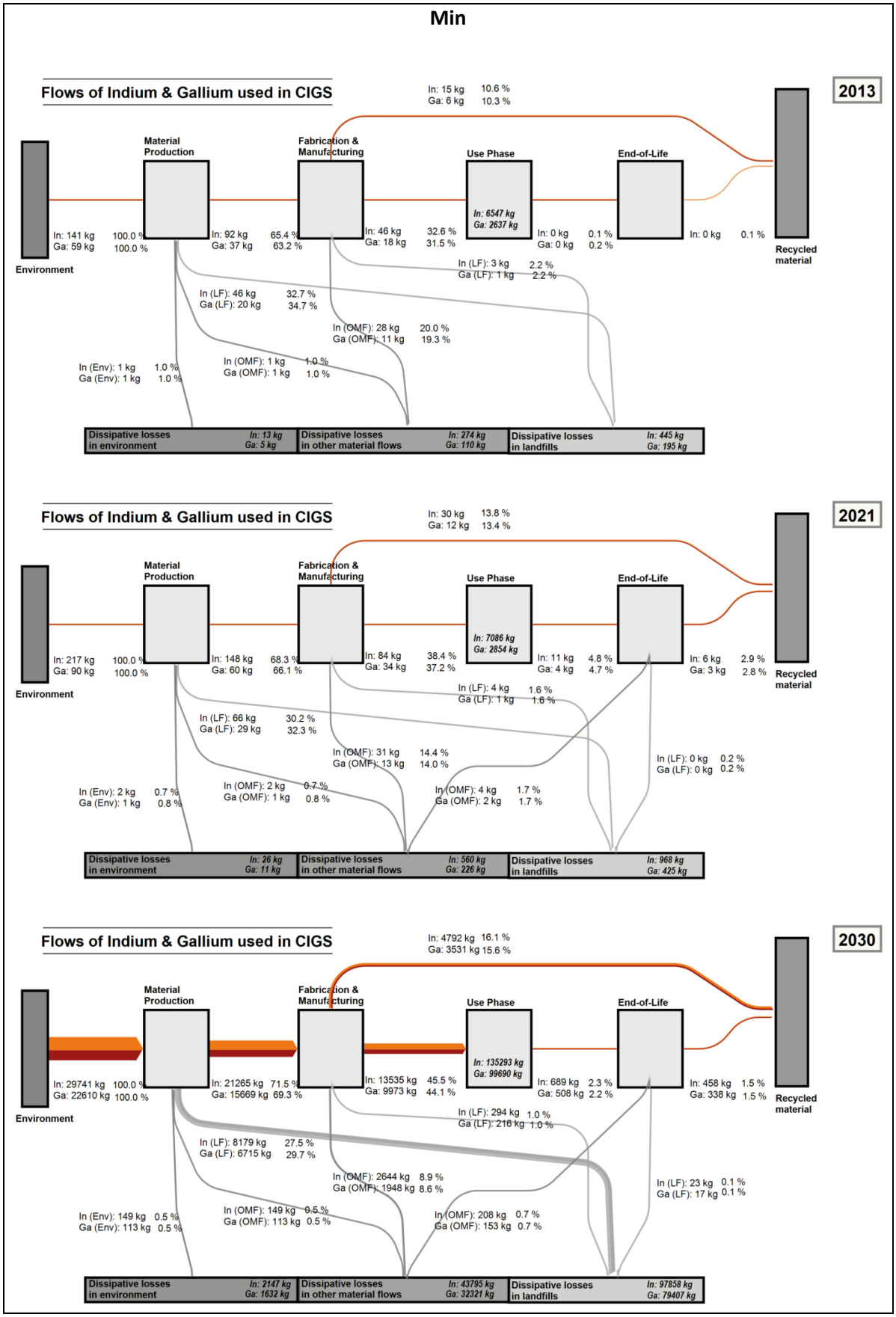


Figure 23: Indium and gallium flows in CIGS MP Scenario A; relative flows refer to input flow from environment (input to material production = 100%); percentages may not add up to 100% due to rounding differences.

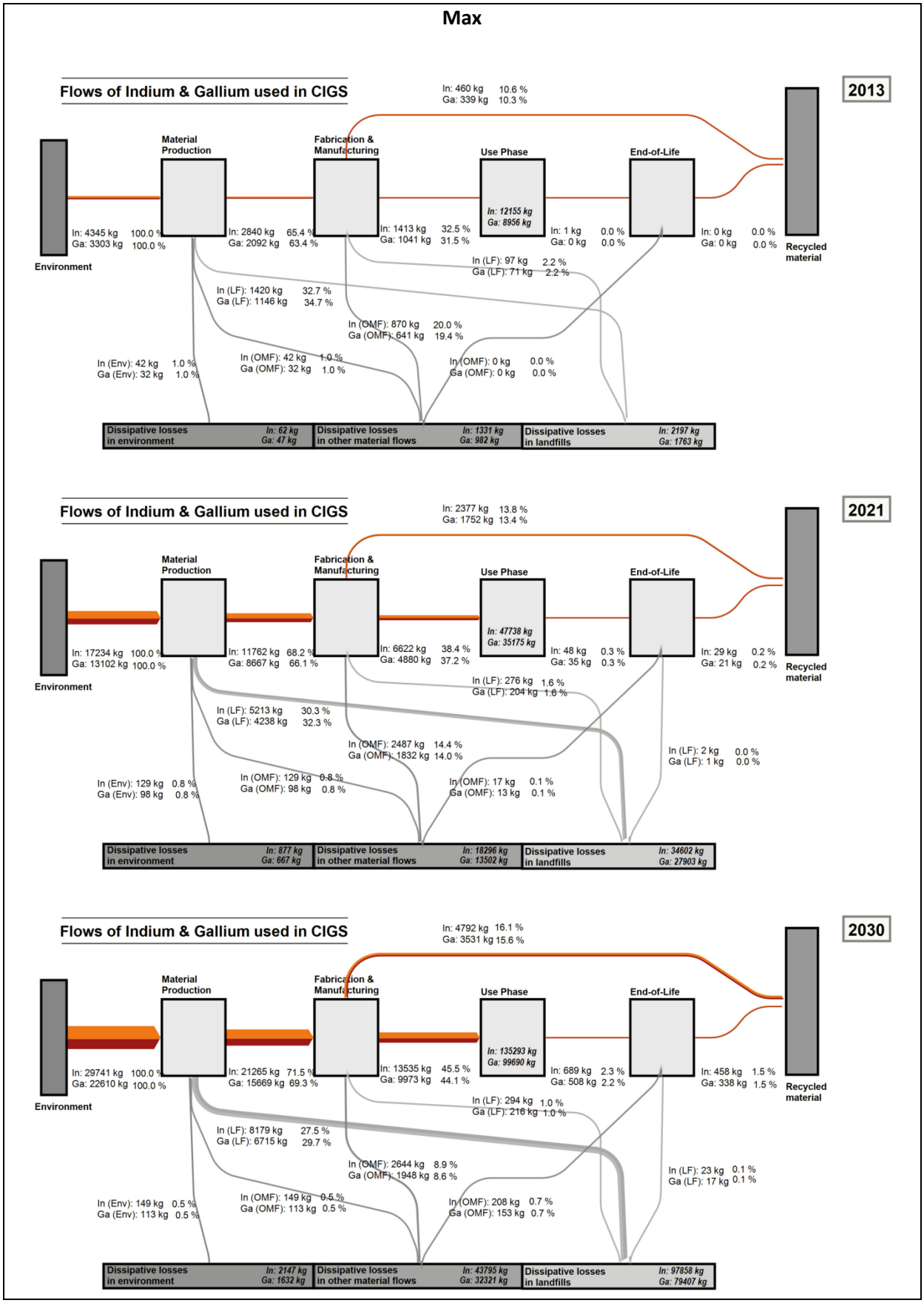


Figure 23 continued.

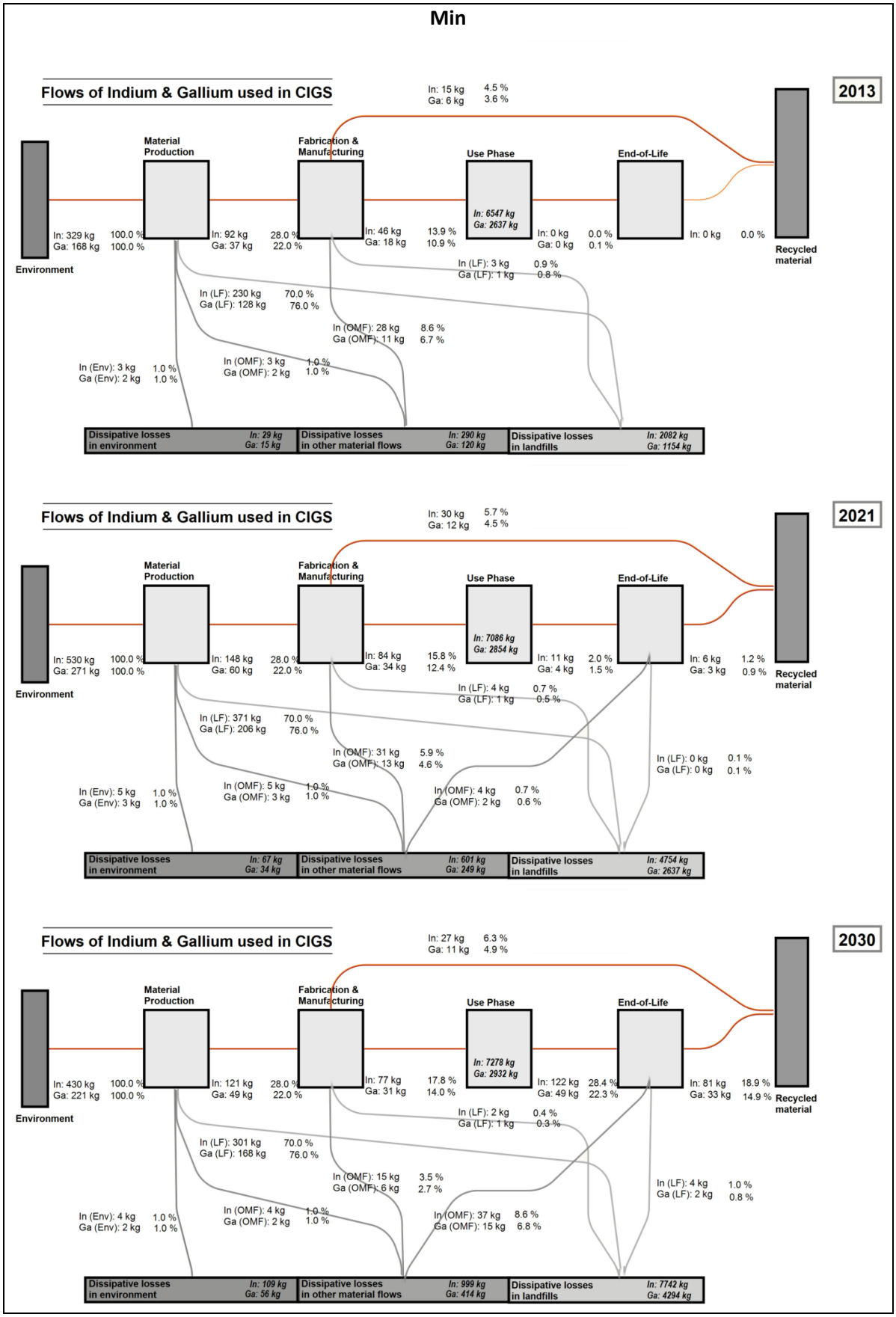


Figure 24: Indium and gallium flows in CIGS MP Scenario C; relative flows refer to input flow from environment (input to material production = 100%); percentages may not add up to 100% due to rounding differences.

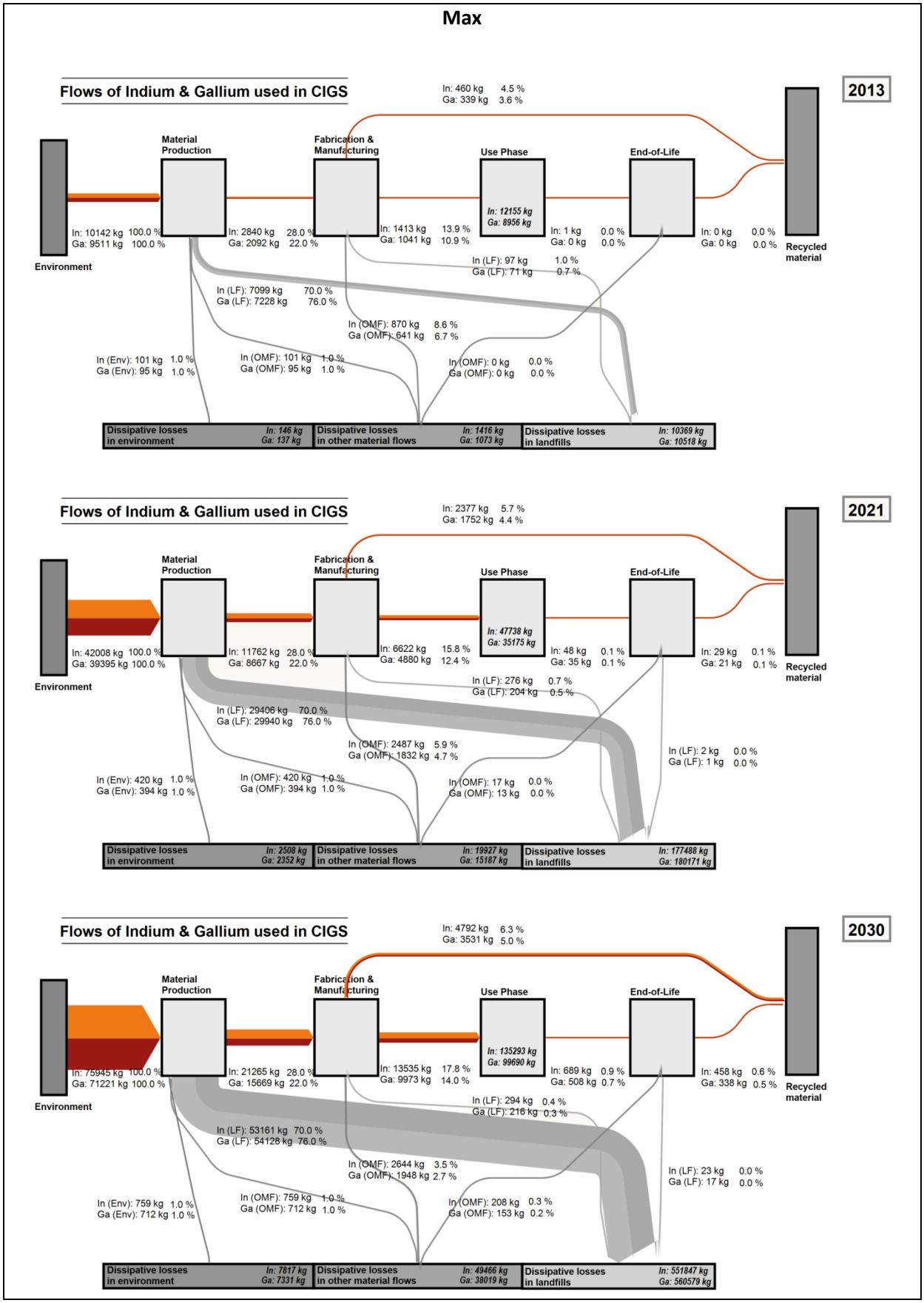


Figure 24 continued.

F&M-I: utilization scenarios

The F&M utilization scenarios show the influence of lower and higher efficiencies in material utilization in F&M. Assuming a lower material utilization (F&M low efficiency scenario) roughly results in a twofold increase of dissipative losses from F&M, mainly to other material flows. CDL are increased by 132 % (min scenario) to 144 % (max scenario). The share of dissipative losses from F&M within the annual dissipation is increased to 39 % in 2012 and 2013 (compared to 30 % in the baseline scenario) and 25 % (min scenario) to 29 % (max scenario) in 2030 for both indium and gallium (compared to 12 % in the baseline scenario).

Throughout the considered timeframe, CDL are increased to 7,612 kg for indium and 3,066 kg for gallium in the min scenario and 491,332 kg for indium and 362,034 kg for gallium in the max scenario. In the high efficiency scenario, dissipative losses from F&M are significantly reduced. In the min scenario, the CDL of indium are reduced to 1,907 kg; CDL of gallium are reduced to 768 kg. In the max scenario, dissipative losses of indium are reduced to 117,934 kg; CDL of gallium are reduced to 86,899 kg.

In the min scenario, in 2012, dissipation from F&M in the annual dissipation amounts to about 15 % for indium and 16 % for gallium, and slowly decreases to 4 % for indium and 3 % for gallium in 2030. In the max scenario, the share of dissipation from F&M decreases from 15 % for both, indium and gallium, in 2012 to about 6 % in 2030. Figure 25 and Figure 26 visualize the material flows in the F&M utilization scenarios.

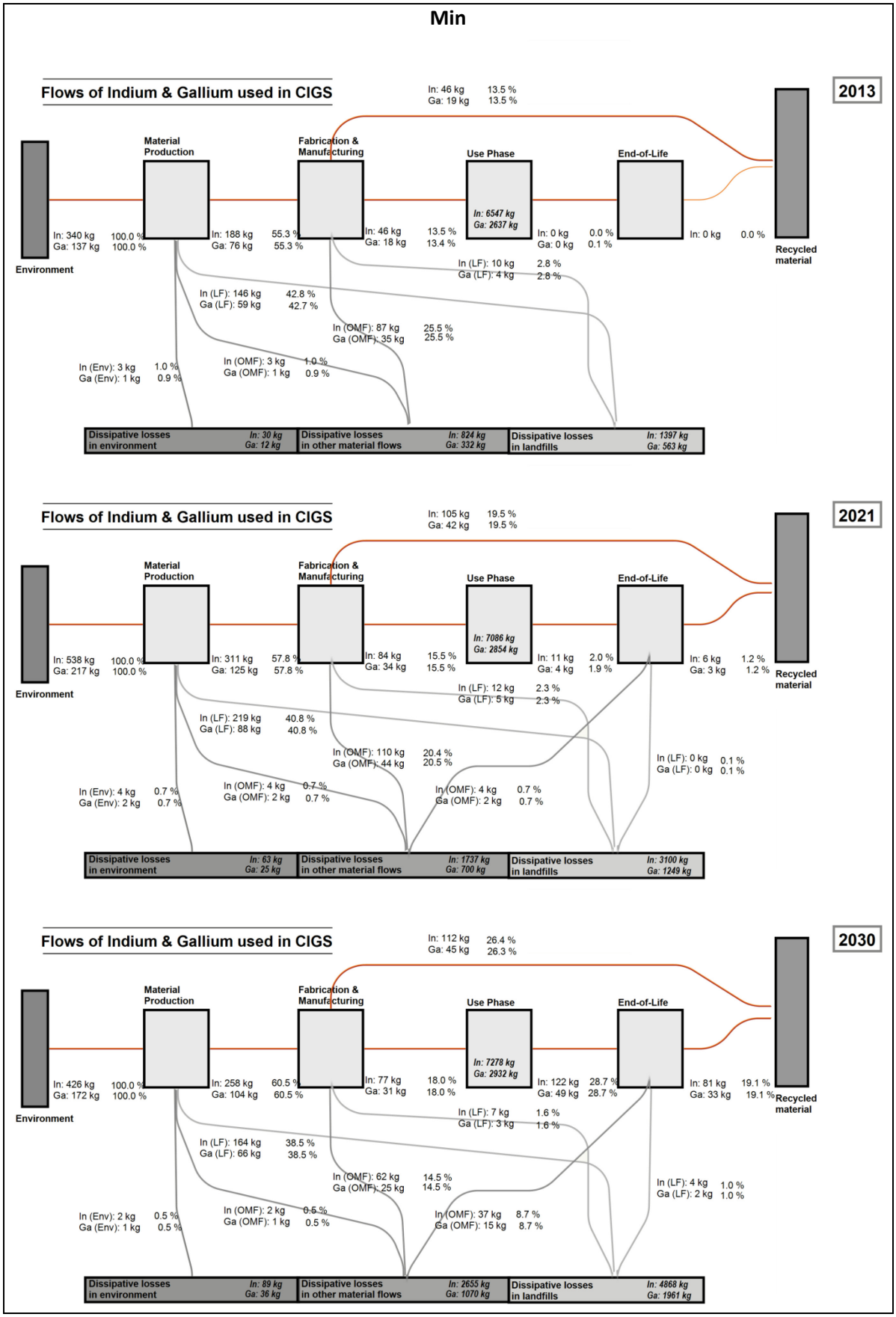


Figure 25: Indium and gallium flows in CIGS F&M-I Low efficiency scenario; relative flows refer to input flow from environment (input to material production = 100%); percentages may not add up to 100% due to rounding differences.

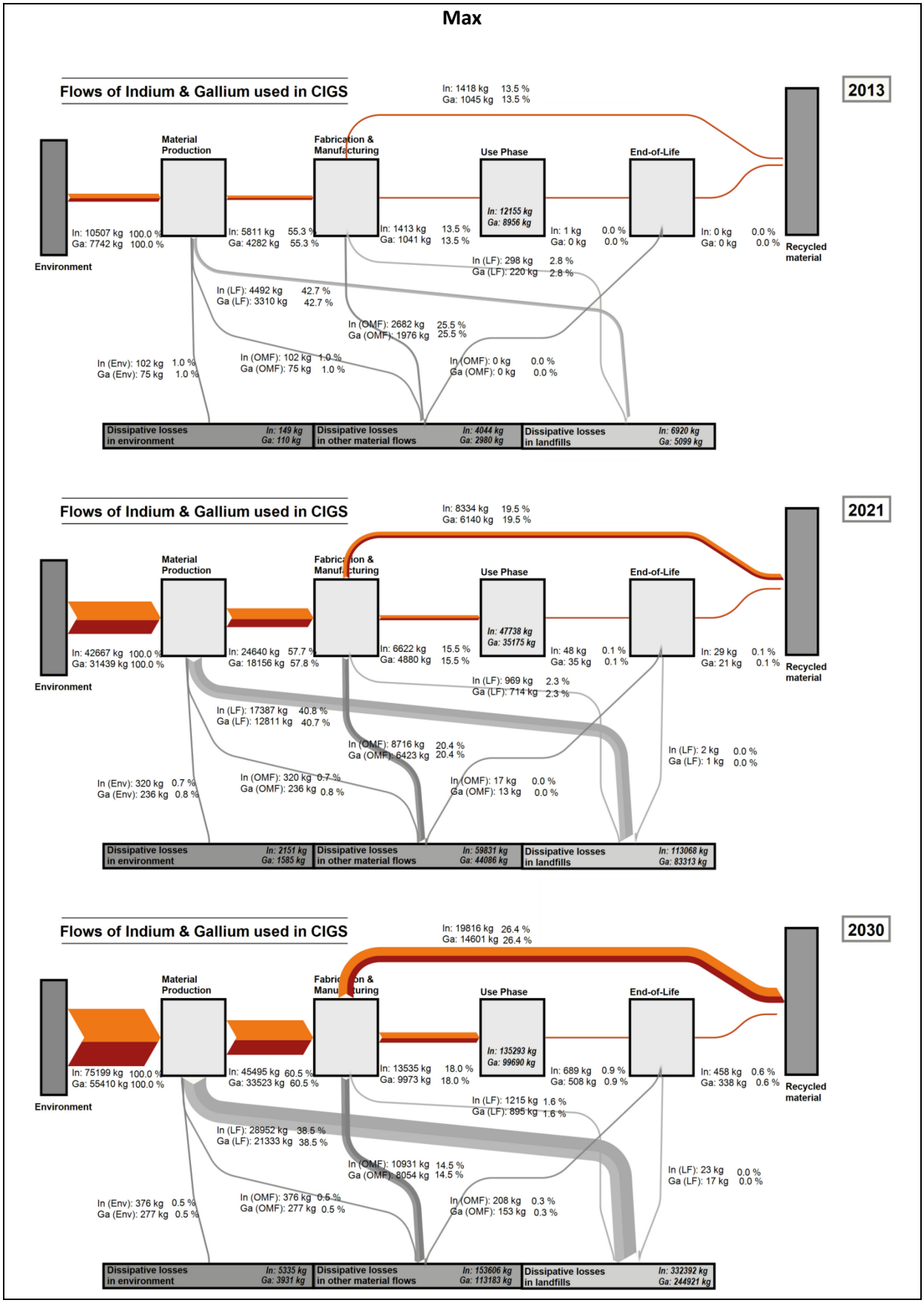


Figure 25 continued.

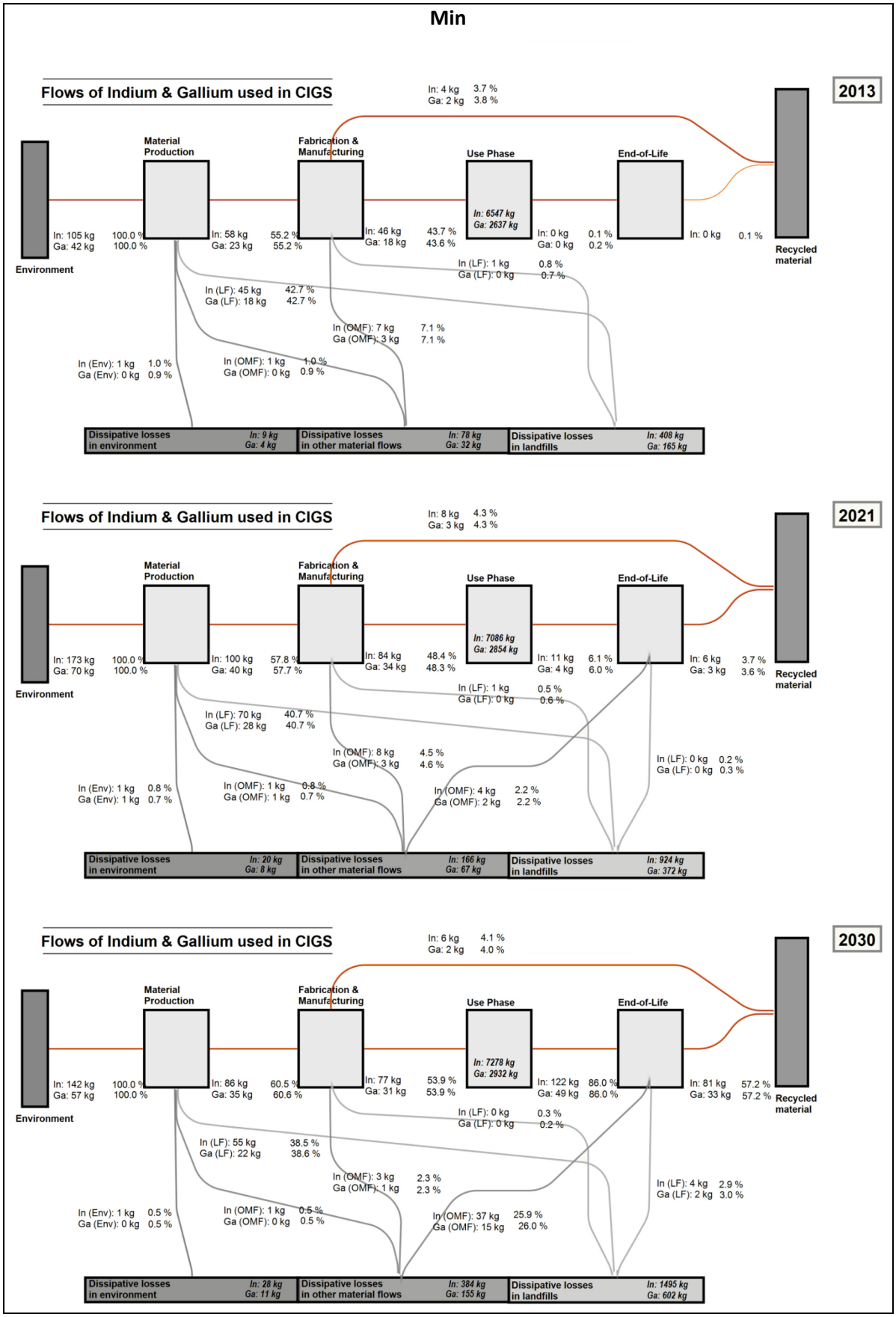


Figure 26: Indium and gallium flows in CIGS F&M-I High efficiency scenario; relative flows refer to input flow from environment (input to material production = 100%); percentages may not add up to 100% due to rounding differences.

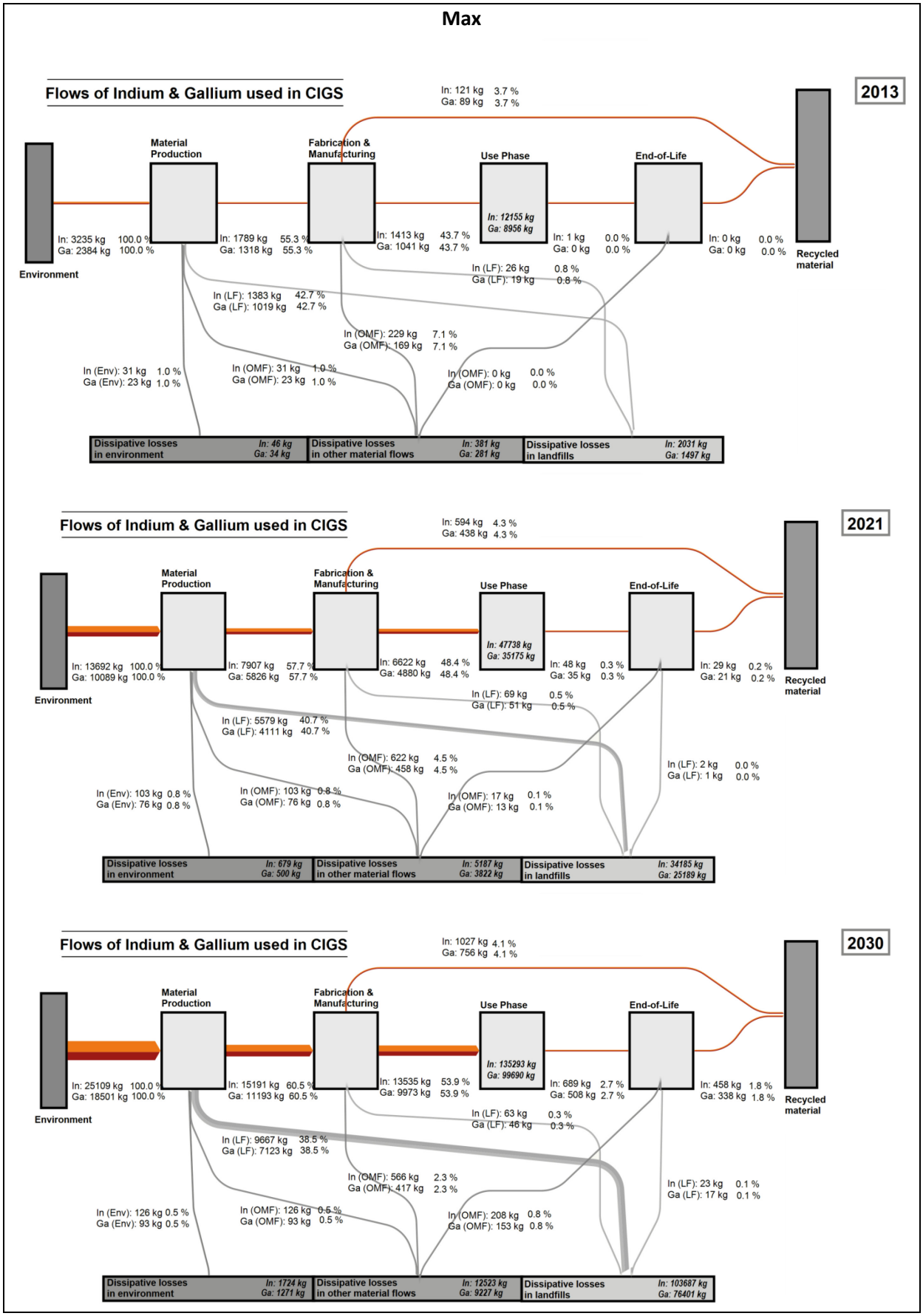


Figure 26 continued.

F&M-II: treatment of production waste

Regarding the treatment of production waste, the recycling rates have been varied in a pessimistic and an optimistic scenario, showing possible variations regarding secondary material flows from F&M.

In the pessimistic scenario, the recycled material flows are slightly decreased compared to the baseline scenario. For the min scenario, the recycled indium flows (from F&M) amount to 14.1 kg in 2013, 27 kg in 2020, and 22.3 kg in 2030. The recycled gallium flows amount to 5.7 kg in 2013, 10.9 kg in 2020, and 9 kg in 2030. For the max scenario, the recycled indium flows amount to 437 kg in 2013, 1,908 kg in 2020, and 3,942 kg in 2030. The recycled gallium flows amount to 322 kg in 2013, 1,306 kg in 2020, and 2,905 kg in 2030.

In the optimistic scenario, the recycled material flows from F&M are slightly increased compared to the baseline scenario. For the min scenario, the recycled indium flows from F&M amount to 16.3 kg in 2013, 36 kg in 2020, and 33.3 kg in 2030; recycled gallium flows from F&M amount to 6.5 kg in 2013, 14.5 kg in 2020, and 13.4 kg in 2030. For the max scenario, recycled indium flows from F&M amount to 502 kg in 2013, 2,544 kg in 2020, and 5,875 kg in 2030. Flows of recycled gallium amount to 370 kg in 2013, 1,875 kg in 2020, and 4,329 kg in 2030.

EOL collection scenarios

In the EOL collection scenarios, variations of the collection rate of 45 % (low collection scenario) and 85 % (high collection scenario) compared to 65 % in the baseline scenario have been analyzed. The low collection scenario results in increased dissipative losses –mainly to other material flows and partly to landfills– and a reduced share of recycled material. For the min scenario, the CDL (2012-2030) of indium amount to 3,326 kg; CDL of gallium amount to 1,340 kg. Compared to the baseline scenario this is a moderate increase by 2 %. For the max scenario, the CDL amounts to 201,586 kg for indium, and 148,537 kg for gallium. Compared to the baseline scenario this is a marginal increase by 0.13 %.

In the high collection scenario, dissipative losses are reduced and recycling is increased. In the min scenario, the CDL of indium amount to 3,257 kg; CDL of gallium amount to 1,312 kg. Compared to the baseline scenario this is a moderate decrease by about 0.6 %. The flows of recycled material from EOL increase from 0.1 kg in 2013 to 83.9 kg in 2030 for indium, and from about 0 kg in 2013 to 33.8 kg in 2030 for gallium.

In the max scenario, the CDL amount to 201,232 kg of indium and 148,276 kg of gallium. This roughly matches the CDL in the baseline scenario. Flows of recycled material from EOL, however, increase from 0.3 kg in 2013 to 473 kg in 2030 for indium and from 0.2 kg to 348 kg for gallium.

EOL recycling scenarios

Regarding the EOL recycling situation, two scenarios have been analyzed. In the no-recycling scenarios EOL recycling quotas have been set to zero. In the high efficiency recycling scenario an increased EOL recycling quota of 95 % is assumed.

In the no recycling scenario, naturally, there are no secondary material flows from EOL. Correspondingly, dissipative losses are increased. In the min scenario, CDL are increased to 3,629 kg for indium and 1,462 kg for gallium. Compared to the baseline scenario this means an increase of 11 % for both, indium and gallium. In the max scenario, CDL amount to 203,188 kg for indium and 149,718 kg for gallium. Compared to the baseline scenario this means an increase of about 1 %.

In the high efficiency recycling scenario, secondary material flows from EOL are increased and dissipation is reduced. In the min scenario, flows of recycled material from EOL amount to 0.1 kg in 2013, 5.7 kg in 2020, and 110.4 kg in 2030 for indium and roughly 0 kg in 2013, 2.3 kg in 2020, and 44.5 kg in 2030 for gallium. CDL amount to 3,150 kg for indium and 1,269 kg for gallium. This means a reduction of about 4 % for both metals compared to the baseline scenario. In the max scenario, flows of recycled material from EOL steadily increase to 622 kg in 2030 for indium and 458 kg for gallium. CDL are reduced to 200,666 kg for indium and 147,859 kg for gallium. In relative terms, however, this only means an increase by 0.2 %.

Summary

In Table 45 the cumulative dissipative losses from 2012 to 2030 are summarized for the different scenarios. The highest improvements in terms of reducing dissipative losses can be achieved by optimizations of the recovery efficiency in MP and by increasing the material utilization in F&M. Increasing the recycling rates in F&M and at EOL, however, only results in moderate improvements, at least within the considered period in time. Due to the long life span of CIGS modules this might change in the future. Also, further increasing EOL collection rates have only a marginal impact on the resulting dissipative losses. The EOL no recycling scenario shows how dissipative losses would be increased without recycling activities, though.

Across the considered scenarios, landfills are the dominating receiving medium for dissipative losses accounting for 60 % to 91 % of the CDL. This is mainly caused by dissipation from the material production stage. Other material flows account for 8 % to 37 % of the CDL. Dissipative losses to other material flows mainly arise in the F&M stage and –particularly in the min scenarios– at EOL. Dissipation to the environment can be considered negligible across all considered scenarios. The distribution of receiving media referring to the CDL is summarized for all scenarios in Table 46. As the values for gallium vary insignificantly from the values for indium, the table shows only the indium values.

Table 45: Summary of cumulative dissipative losses in different CIGS scenarios

		Cumulative dissipative losses [kg]				Change from baseline scenario			
		Min		Max		Min		Max	
		In	Ga	In	Ga	In	Ga	In	Ga
Baseline scenario		3,276	1,320	201,330	148,348	-	-	-	-
Material production	A	2,454	1,046	143,800	113,359	-25%	-21%	-29%	-24%
	C	8,850	4,764	609,130	605,930	170%	261%	203%	308%
F&M material utilization	low efficiency	7,612	3,066	491,332	362,034	132%	132%	144%	144%
	high efficiency	1,907	768	117,934	86,899	-42%	-42%	-41%	-41%
F&M treatment of production waste	pessimistic	3,342	1,346	207,949	153,226	2%	2%	3%	3%
	optimistic	3,184	1,283	192,598	141,915	-3%	-3%	-4%	-4%
EOL collection	low collection	3,326	1,340	201,586	148,537	2%	2%	0%	0%
	high collection	3,257	1,312	201,232	148,276	-1%	-1%	0%	0%
EOL recycling	no recycling	3,629	1,462	203,188	149,718	11%	11%	1%	1%
	high efficiency recycling	3,150	1,269	200,666	147,859	-4%	-4%	0%	0%

Table 46: Distribution of CDL to receiving media (Env=Environment; OMF=Other material flows; LF=Landfills). The table only shows the values for indium, the gallium values vary insignificantly.

		Min			Max		
		In			In		
		Env	OMF	LF	Env	OMF	LF
Baseline scenario		1.3%	28.5%	70.2%	1.3%	21.9%	76.8%
Material production	A	1.5%	37.7%	60.8%	1.5%	30.5%	68.1%
	C	1.2%	11.3%	87.5%	1.3%	8.1%	90.6%
F&M material utilization	low efficiency	1.2%	34.9%	64.0%	1.1%	31.3%	67.7%
	high efficiency	1.5%	20.1%	78.4%	1.5%	10.6%	87.9%
F&M treatment of production waste	pessimistic	1.3%	29.7%	69.1%	1.2%	24.1%	74.7%
	optimistic	1.3%	26.7%	72.0%	1.3%	18.9%	79.8%
EOL collection	low collection	1.3%	29.4%	69.3%	1.3%	22.0%	76.7%
	high collection	1.3%	28.1%	70.6%	1.3%	21.9%	76.8%
EOL recycling	no recycling	1.2%	34.4%	64.4%	1.2%	22.6%	76.2%
	high efficiency recycling	1.4%	26.0%	72.7%	1.3%	21.7%	77.0%

5.2.7 Conclusions & Discussion

The majority of indium and gallium used in CIGS photovoltaic cells dissipates along the life cycle. Still, an increasing share is recycled from F&M and EOL. The main hot spot in terms of dissipation within the life cycle is the material production stage followed by the F&M stage.

The dissipative losses mainly end up on landfills, followed by other material flows –to a large extent ashes and slags used as construction or filling material. This indicates a theoretically large potential for urban and landfill mining activities. In the baseline max scenario, the cumulative dissipative losses of indium to landfills and other material flows amount to 198,792 kg, the cumulative dissipative losses of gallium to landfills and other material flows amount to 146,478 kg. Comparing these amounts to the 2012 global production of the metals (cf. section 5.1) emphasizes their scale: The cumulative

losses of indium to landfills and other material flows amount to 25 % of the 2012 world production, the cumulative losses of gallium to the same media amount to 41 %. For gallium, this means that the amount potentially available for urban and landfill mining is –in the max scenario– 1.8 to 2.8 times bigger than the 2012 domestic consumption (cf. section 5.1.2). For indium, this means that –in the max scenario– deployment of CIGS PV cells in Germany alone results in dissipative losses to other material flows and landfills that amount to about 1.8 % of the known global reserves. In the min scenarios, the absolute dissipative losses are significantly lower as described in the results section, but the actual development is likely to be located somewhere between these two extremes. It needs to be mentioned, though, that in great part these losses occur outside of Germany –as the life cycle stages of MP and F&M are in great part located elsewhere.

Independently from the analyzed product, the material production processes of indium and gallium generally result in major losses implying a great potential for process optimization and landfill mining. The alternative MP scenario (A) showed how dissipation could be reduced through technological improvement in primary production. MP scenario C, in which the system boundaries have been expanded including losses resulting from the processing of zinc ores without indium recovery and bauxite processing without gallium recovery, showed the general inefficiency in the processing of the respective ores. Vice versa, a big potential for reducing dissipative losses and increasing the primary production of indium and gallium can be identified. So far, however, it has not been economic to install the additional indium extraction capacity at zinc refineries (Graedel, Gunn, and Tercero Espinoza 2014). Future increases in the price may increase economic incentives. Through public funding economic incentives could be further enhanced. While the production of indium and gallium as by-products is often considered as a problem within their supply situation (cf. section 5.1), it can be said that by installing additional extraction capacity their supply could be increased significantly without altering the production amounts of the carrier metals.

Regarding more efficient F&M processes, it has to be noted that highly efficient processes exist in laboratory scale. If these processes get applied in the future, significant reductions of dissipation will be possible. In the long run, increasing recycling should get higher attention. Although increasing recycling rates did not result in very high reductions of dissipation for the considered time span, there is a substantial building of material stocks that will result in waste flows with some delay. Also in F&M, increasing recycling rates could be an strategy together with increasing material utilization in order to avoid material dissipation.

Particularly for Germany, the development of in-use stocks and secondary material flows (output flows from EOL), implies a growing necessity for a working recycling infrastructure. Although the importance of efficient recycling processes has already been shown in the analyzed scenarios, it will be significantly increased in the years following the considered timespan as indicated by the in-use stock development. In the case of very moderate growth rates (e.g., in the baseline min scenario), the material demand could be covered by recycling secondary material already within the considered timespan. While all major deposits of indium and gallium are located outside of Germany (cf. section

5.1.1 and 5.1.2), recycling of secondary material flows from F&M (if located in Germany) and EOL provides the chance of reducing the dependency on resource imports.

Regarding the modelling approach, it has to be noted that the parameters in the different scenarios have been varied independently from each other. Hereby, the influence of the different parameters could be identified but possible connections between the different parameters are neglected. This concerns particularly the application of recycling processes. There is an obvious connection between waste amounts and feasibility of recycling processes; higher waste amounts may increase the feasibility of certain recycling processes in terms of economy of scale. Before any recycling activity will be carried out, a certain threshold in terms of size of secondary material flows needs to be reached.

Major variations of results arise from the underlying expansion scenarios. The assumed PV installations in the min and max scenario which represent the range of installations assumed in different expansion scenarios differ significantly. As it can be seen from the past, the PV market is particularly volatile and subject to political decisions. Against this background, analyzing potential future developments in their entire range appears indicated in order to visualize the space in which future development may take place. This uncertainty regarding the future development cannot be resolved.

Overall, the importance of political decisions on the future manifestation of the CIGS life cycle has to be emphasized. Besides the absolute installations, political decisions influence the treatment of production and end-of-life waste. So far, the development of recycling processes has at least partly been funded by public agencies. The future availability of feasible recycling processes may rely on the continuation of these funding activities. Also collection of end-of-life modules and quotas and regulations regarding their further treatment are subject to political decisions.

5.3 POLYMERIZATION CATALYSTS

Germanium dioxide (GeO_2) –among other materials– is used as a catalyst in polymerization processes in the production of bottle-grade PET. Contrary to indium and gallium in CIGS PV cells, germanium in polymerization catalysts has received almost no attention with regard to the study of material flows.

Details on the polymerization process are given for example by Roewer (2014) or Pang, Kotek, and Tonelli (2006). Antimony and titanium are alternative catalysts in PET manufacturing, and antimony accounts for the majority of the market. PET manufactured using GeO_2 catalysts is used for drink bottles and shows particularly good properties in terms of brightness and shine.

Contrary to the other products under study, germanium bearing polymerization catalysts are used in the production of another end-product, i.e., in the production of bottle-grade PET or PET bottles (as the end-product), respectively. This means that the use phase of the considered product is actually the production phase of another product. Regarding the material flows along the life cycle, the subsequent phases (use of PET and PET bottles, respectively) are also of importance. Therefore, in addition to the use phase of the polymerization catalysts (i.e., PET production), the system boundaries are expanded and the production and use of PET bottles are studied, too, to get a better understanding of the fate of germanium dissipating in the use phase of polymerization catalysts. The geographic focus (products used in Germany) is hereby applied to PET bottles, while the use phase of the polymerization catalysts (i.e., the production of bottle grade PET) can be located elsewhere[55].

5.3.1 MATERIAL PRODUCTION STAGE: GERMANIUM PRODUCTION

As described in section 5.1.3, in principle, germanium can be produced from a variety of sources. The zinc ore sphalerite (zinc blende) is frequently reported to be the main source, followed by the recovery from coal fly ashes and the co-production in copper and lead processing (Roewer 2014; USGS 2014; Guberman 2013; Arroyo et al. 2009; Moskalyk 2004). Melcher and Buchholz (2014) quantify the share of the processing of coal ashes to about 30 to 50 % while the recovery of germanium in copper and lead production is negligible, i.e., processing of zinc ores accounts for the balance of about 50 to 70 %. Based on this, the recovery from zinc ores and the recovery from coal fly ashes are considered as the two dominant routes in germanium production. Still, for both routes data availability is very limited.

The process design in both routes is essentially the same (Melcher and Buchholz 2014). Figure 27 shows the germanium recovery from hydrometallurgical zinc processing but also shows potential other sources such as coal ashes. In hydrometallurgical zinc processing some elements, including germanium, are intolerable contaminants and must be removed prior to zinc extraction processes. This can be done by fractional distillation of $GeCl_4$ or other processes (e.g., flotation, adsorption onto activated carbon, solvent extraction) (Arroyo et al. 2009; Höll, Kling, and Schroll 2007).

[55] PET production is widely distributed over the globe–about 24 % is produced in China, 20 % in the EU, 20 % in Canada, Mexica, and the U.S., and 16 % in the rest of Asia (PlasticsEurope 2013). The majority of imports to the EU comes from Asia, though (M. Neal, pers. comm.).

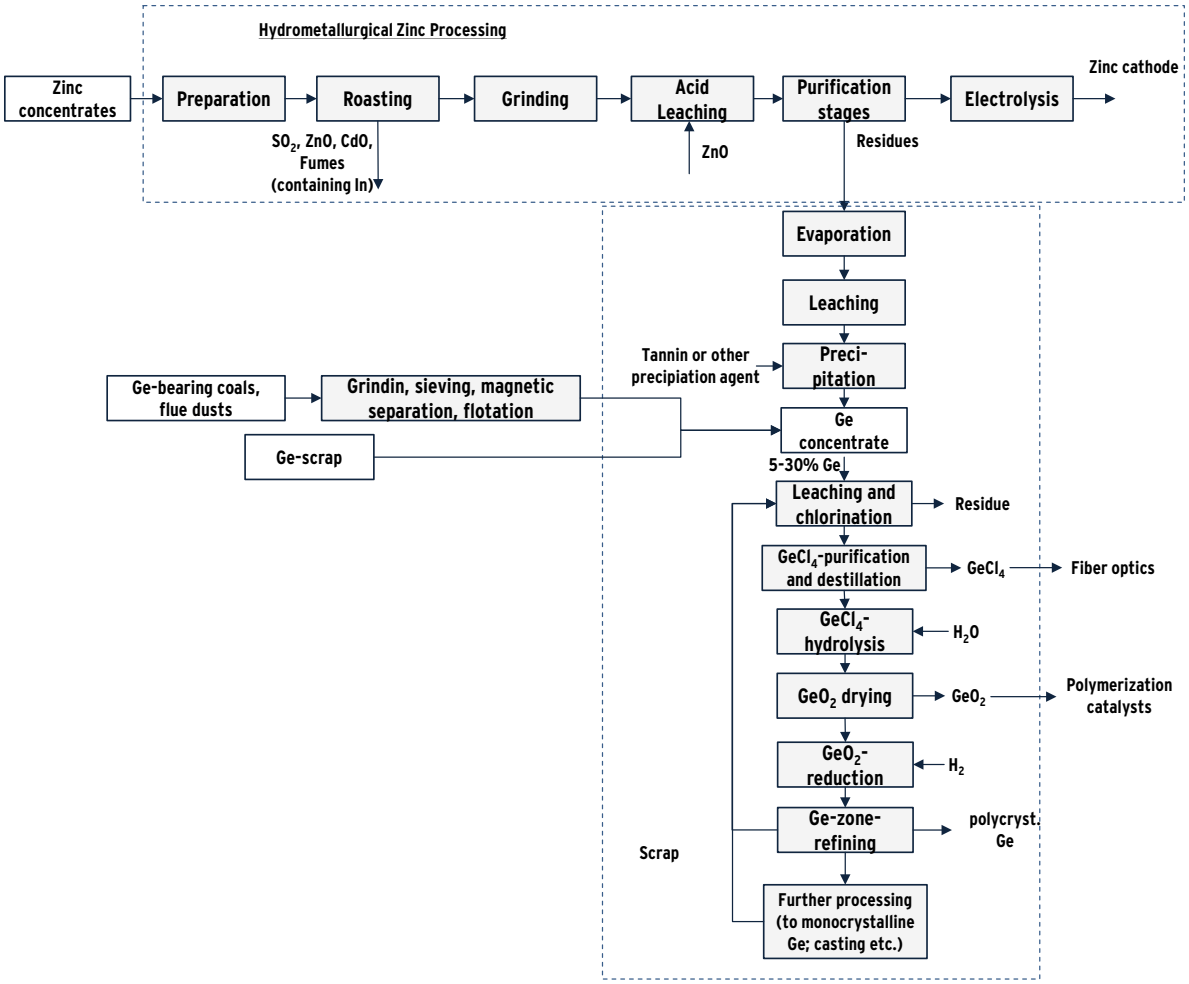


Figure 27: Hydrometallurgical zinc processing and exemplary germanium recovery route (zinc processing based on information from Wittmer et al. 2011; Fthenakis, Wang, and Kim 2009; Bräutigam et al. 2008; Alfantazi and Moskalyk 2003; germanium recovery process based on Roewer 2014; Melcher and Buchholz 2014; Fthenakis, Wang, and Kim 2009; alternative process designs for germanium recovery are described in, e.g., Wang, Peng, and Zhang 2011; Li et al. 2011; Arroyo et al. 2009)

The production of germanium generally consists of two main stages. Firstly, the germanium concentrate is produced which is then further processed into germanium end products (Fthenakis, Wang, and Kim 2009; Moskalyk 2004). Mainly hydrometallurgical processes are used for germanium recovery. These processes are based on the precipitation of germanium concentrate with tannic acid or other precipitation agents. Germanium tetrachloride is hydrolyzed to the dioxide and then reduced to pure metals by means of either carbon, or hydrogen (Arroyo et al. 2009; Fthenakis, Wang, and Kim 2009; Höll, Kling, and Schroll 2007; Moskalyk 2004). For applications that require GeO_2 instead of pure germanium the steps of reduction and refining can be omitted. The germanium dioxide can be used directly for applications such as polymerization catalysts (Roewer 2014; Melcher and Buchholz 2014).

Based on the literature, recovery rates of germanium for process routes as described above seem to vary quite a bit. The reported recovery rates include 50 % (Wang, Peng, and Zhang 2011), about 85 % (Wang, Peng, and Zhang 2011), 89 % (Fayram and Anderson 2008), and go up to over 90 % (Li et al. 2011; Zhou, Zhong, and Zheng 1989). Kul and Topkaya (2008) show the dependency of germanium

recovery rates on different process parameters such as duration of leaching, acid concentration, temperature, and solid-liquid ratio. For optimized conditions they report a recovery rate of 92.7 %. Regarding the low recovery rates of 50 % reported by Wang, Peng, and Zhang (2011), the authors mention that through process optimizations rates above 90 % are achievable. I.e., despite the existing uncertainties, recovery rates between 85 % and 90 % seem to be rather likely. Against this background and due to the lack of more accurate data, a recovery rate of 85 % and resulting losses of 15 % are assumed for the baseline scenario (scenario A), as a conservative assumption. Additional losses from the reduction step (GeO_2 to Ge) –which is applied for the production of pure germanium for other applications– are nowhere reported in the literature. These losses are, however, irrelevant regarding the product-centric analysis of GeO_2 used in polymerization catalysts. The process residues (i.e., the material losses) from the respective process routes are usually landfilled. Regarding the recovery from coal ashes, Arroyo et al. (2009) report even higher recovery rates of 96 % to 100 %.

While the efficiencies in germanium recovery are relatively high, only a minor share of zinc ores and germanium bearing coal ashes is treated regarding recovery of germanium. For example, according to expert information, there is no zinc plant in Europe which performs germanium recovery. Respective plants have been shut down for economic and environmental reasons (R. Rodermund, pers. comm.). Thus, significant losses arise from germanium sources treated in process routes not aiming at a germanium recovery. Data on the quantity of these losses is not available, but an estimation can be conducted based on the processing of zinc ores. As described in section 4.7, the consideration of these losses means an expansion of the defined system boundaries. Still, valuable information can be obtained by including these losses in the analysis. Although data availability does not allow including all potential germanium bearing sources such as coal (ashes), cassiterite, or hematite (cf. section 5.1.3), the expansion to zinc blende ore processing already provides a clear picture of the inefficiencies and occurring losses in the material production stage.

For germanium produced as a by-product in zinc processing, zinc blende ores are the main source. 95 % of all primary zinc is produced from zinc blende ores (IZA 2011). In these ores, the average germanium content is about 0.01 wt.-% (Roewer 2014; Melcher and Buchholz 2014) and the zinc content is between 5 and 15 wt.-% (IZA 2011). Assuming further an efficiency in zinc production of 85 % (Lauwigi and Dressler 2011), an annual zinc production of 13,500 Gg in 2012 and 2013 (USGS 2014), and an efficiency of 80 % to 90 % in germanium recovery, a theoretical germanium production as by-product from zinc production of about 8 Gg germanium can be calculated. The consideration of the actual production of germanium in 2012 and 2013 results in losses of about 98 % in the germanium recovery from zinc ores.

Required data on total exploitation of germanium bearing coals for a respective estimation of the losses in the germanium recovery from coal ashes has not been available. Information from Melcher and Buchholz (2014), however, indicates rather high losses as well, as there are various coal deposits with relevant germanium contents all over the world, while the recovery from coal ashes currently appears to be limited to China and Russia. In principal, germanium recovery from coal ashes contain-

ing 0.5 % to 1 % germanium has been proven to be feasible, though. Based on the high losses in the zinc production route and with regard to the uncertainties concerning the coal ashes processing route, an alternative scenario (scenario B) with losses of about 90 % in the material production stage is analyzed. Future analyses might also consider the variety of potential germanium bearing ores (iron ores, tin ores, etc.; see Table 26) that are so far not treated regarding a germanium recovery at all, if the required data can be obtained. The scenarios for the material production stage of germanium are summarized in Table 47.

Table 47: Germanium losses from material production stage

		2012 A	2012 B[56]	2030 A	2030 B
Dissipative losses	L_{MP}	15%	90%	10%	90%
- **to the environment**	$L_{MP,env}$	0.5%	1%	0.25%	1%
- **to other material flows**	$L_{MP,omf}$	0.5%	1%	0.25%	1%
- **to landfills**	$L_{MP,lf}$	14%	88%	9.5%	88%

5.3.2 Fabrication & Manufacturing of Polymerization Catalysts

As described, GeO_2 is an intermediate product in the production of pure germanium. According to Roewer (2014) and Melcher and Buchholz (2014) it can be used directly for the application in polymerization catalysts, thus, no relevant additional losses occur in the stage of F&M. The catalysts are 100 % GeO_2 (Roewer 2014; Teck 2014; J. F. Riecken, pers. comm.), i.e., about 69 wt.-% are germanium. Based on this as well as on additional consultation of experts (G. Roewer, pers. comm.), the losses in F&M are considered to be negligible (see Table 48). Here, no changes are assumed regarding the future development until 2030.

Table 48: Germanium losses from F&M of polymerization catalysts

Flow		**2012**	**2030**
Recycled shares from fabrication & manufacturing	R_{FM}	0%	0%
Total dissipative losses from fabrication & manufacturing	L_{FM}	0%	0%

5.3.3 Use Phase of Polymerization Catalysts: Production of Bottle-Grade PET

PET (polyethylene terephthalate) is produced from ethylene glycol and terephtalic acid and dimethyl terephthalate. The polymerization proceeds in two steps, esterification and condensation reaction (Pang, Kotek, and Tonelli 2006; Westerhoff et al. 2008). Further details on PET production are given by Pang, Kotek, and Tonelli (2006). In the polymerization, GeO_2 is used as a catalyst in the second step of the polymerization process (Roewer 2014).

Alternative catalysts are titanium or antimony (as diantimony trioxide) (Pang, Kotek, and Tonelli 2006; European Commission 2008). Each catalyst material has its specific characteristics that need to be considered in the catalyst choice. Germanium is quite costly as a catalyst material (Westerhoff et

[56] A described in the text, for scenario B the system boundaries are extended, including material losses that are not related to the production of germanium dioxide used for polymerization catalysts.

al. 2008) but results in particularly good properties in terms of brightness, transparency/clarity, and shine as well as higher hotfill temperatures (Oakdene Hollins 2011; Teck 2014). PET produced with other catalysts on the other hand tends to become opaque (Roewer 2014). Titanium-based catalysts impart a yellow color to the PET (Pang, Kotek, and Tonelli 2006), while antimony-catalysts tend to cause a grey discoloration of PET (Aharoni 1998).

Generally, a share of antimony catalysts of 90 % in PET production has been reported in several publications over several years (Westerhoff et al. 2008; Shotyk and Krachler 2007; Thiele 2004; Thiele 2001). In addition, Guberman (2013) reports that in the U.S. germanium bearing catalysts are not used in PET production at all, and that also generally the use of germanium in PET production is steadily declining due to lower costs of antimony and titanium based catalysts (Guberman 2013). Erdmann and Behrendt (2011), however, indicate that in the food and beverage industry GeO_2 still is the leading catalysts due to higher quality requirements. This continuing importance of GeO_2 as a catalyst is also underlined by statistics on germanium's applications where polymerization catalysts have been a major field of application for years. Specifically for Japan, a high importance of GeO_2 catalysts is frequently reported (e.g., Guberman 2013; RPA 2012; Oakdene Hollins 2011) and also information from a manufacturer indicates that the majority of germanium consumption for catalysts comes from manufacturers located in Asia (J. F. Riecken, pers. comm.). In the rest of the world (with the U.S. being an exception according to Guberman 2013), germanium is still used in quantities sufficient to impart characteristics such as brightness and shine (Oakdene Hollins 2011). Also data on germanium traces in PET bottled drinking water indicates a relevance of germanium based polymerization catalysts particularly for Japan, France, and Germany (Westerhoff et al. 2008). Information from the Committee of PET Manufacturers in Europe (CPME) (M. Neal, pers. comm.), however, confirmed the dominance of antimony catalysts in Europe, but also confirmed the use of germanium catalysts in a smaller scale in Europe as well as in the production of PET imported to Europe that in its majority comes from Asia and the Middle East. Assuming a share of germanium catalysts in the production of bottle-grade PET of 5 % to 10 % has been considered reasonable by the CPME (M. Neal, pers. comm.). Based on this a range of 5 % to 10 % for the share of GeO_2 catalysts in PET production is analyzed in the model.

In the production process, the polymerization catalyst dissipates completely into the product and is not recovered (Roewer 2014; Landesanstalt für Umwelt 2012; Oakdene Hollins 2011; Hassan 2003; Hassan 2001). Hence, in the use phase 100 % of the embodied germanium dissipates into the product, i.e. into the PET. Thus, a complete dissipation into other material flows can be observed in the use phase of polymerization catalysts (see Table 49).

Table 49: Dissipative losses of germanium from use phase of polymerization catalysts

		2012	2030
Dissipative losses from use phase	L_{Use}	100%	100%
- **to other material flows**	$L_{Use,omf}$	100%	100%

Further fate after dissipation to other material flows

The further fate of the dissipated material can be analyzed by looking at the receiving material flow –bottle grade PET resin and finally PET beverage bottles. Also, since data referring to the amount of germanium used in polymerization catalysts for the German market is unknown, the amount of germanium will be determined based on the amount of PET used for beverage packaging per year and the average concentration of GeO_2 in PET bottles.

The amount of PET used for beverage packaging per year and the resulting germanium amount is subject to the following parameters:

- The specific germanium concentration in PET;
- beverage consumption per year;
- shares of different bottles types (one-way and returnable bottles; shares of different bottles sizes);
- the specific weight per bottle (amount of PET per volume of beverage).

Germanium concentration in PET

Data regarding the GeO_2 concentration in PET produced using GeO_2 catalysts ranges from 1:10.000 (Hassan 2003) to 1:100,000 to 7:100,000 (Oakdene Hollins 2011) or 10 to 70 mg/kg, respectively. Analyses done by the CPME showed (elemental) germanium concentrations of 10 to 80 mg/kg and an average concentration of 34 mg/kg (corresponding to a GeO_2 concentration of about 49 mg/kg) (M. Neal, pers. comm.). This average concentration is relatively close to the 40 mg/kg given as an average by Oakdene Hollins (2011) which has been used in (Zimmermann and Gößling-Reisemann 2014a). Following this, the range of the average values, i.e., a range of 40 to 49 mg GeO_2 per kg PET and 27.6 to 34 mg Ge per kg PET, respectively, will be analyzed in the model.

Beverage consumption

Data on beverage consumption from refund-bottles is available from (Heinisch 2011). In addition, non-refundable beverage packaging has not been considered by Heinisch (2011), but needs to be considered in the analysis. Here, non-disclosed data from the German Federal Environment Agency (Umweltbundesamt) has been available (cf. Zimmermann and Gößling-Reisemann 2014b). This data indicates an additional amount of beverages between 1.000 and 1.800 million liters per year. For the calculation an average amount of 1.400 million liters is assumed. As beer and shandy are only sold in refund bottles in Germany, this amount is divided 50:50 and added to water and soft drinks.

The respective data for the years 2004 to 2009 as well as the data used in the model are given in Table 50. As it can be seen, for beer and shandy, water and soft drinks the consumption is relatively constant across different years, with maximum deviations of 2.8 % for beer and shandy and about 8 % for water and soft drinks. Only for mixed drinks a significant decline of consumption from 2004 to 2006 can be observed which is likely to be caused by new packaging regulations (“3. Novelle der VerpackV”) (Zimmermann and Gößling-Reisemann 2014b). From 2006 on, however, the consumption

seems to stabilize around 6 million liters. Still, PET packaging is irrelevant for these drinks (Heinisch 2011), and therefore no further consideration is necessary. Regarding the other beverage types, the average consumption values are used and deviations of ±10 % are considered.

Table 50: Beverage consumption in Germany (based on Heinisch 2011) [data in million liter]

Beverage type	2004	2005	2006	2007	2008	2009	Mean[57]	Deviation (used in model)
Beer and shandy	7,429.4	7,354.0	7,510.4	7,547.0	7,425.6	7,343.5	7,435.0	±10%
Water	12,247.8	12,369.7	12,995.6	13,253.0	13,131.6	13,204.5	13,567.0	
Soft drinks	10,557.3	10,740.6	11,131.7	11,301.1	11,432.2	11,288.3	11,775.2	
Mixed drinks	54.4	13.3	6.8	5.9	6.0	6.3	15.5	
Total	**30,288.9**	**30,477.6**	**31,644.5**	**32,107.0**	**31,995.4**	**31,842.6**	**33,792.7**	

Shares of different packaging types

The beverage consumption data refers to the total consumption of beverages, i.e. it includes any type of packaging including PET. Therefore, the shares of the different packaging types need to be considered. The respective data is available from (Heinisch 2011) and is shown in Table 51. Among PET bottles, refillable and one-way bottles can be distinguished. Concerning beer, refillable PET bottles are not used at all; one-way PET bottles are of little relevance (4.1 % to 6.8 %). Regarding 2030, a share of one-way PET of 7 % is assumed. For water the share of refillable PET bottles varies between 18.4 % and 21.1 % and the share of one-way PET bottles increased from 31.5 % in 2004 to 56.1 % in 2009. For soft drinks a declining share of refillable PET bottles from 27.5 % in 2004 to 20.5 % in 2009 can be observed while the share of one-way PET bottles increased from 33.7 % to 60.5 % (Heinisch 2011). This trend towards one-way PET bottles is well-documented and likely to continue (Umweltbundesamt 2011). Based on this, a share of one-way PET bottles of 75 % and of refillable bottles of 15 % in 2030 for water and soft drinks is assumed (cf. Zimmermann and Gößling-Reisemann 2014a; Zimmermann and Gößling-Reisemann 2014b). The corresponding beverage amounts can be found in Appendix B) in Table A 47.

[57] Including non-refund beverages added to water and soft drinks.

Table 51: Shares of PET packaging for different beverage types (2004-2009 data from Heinisch 2011; 2030 assumptions according to Zimmermann and Gößling-Reisemann 2014a; Zimmermann and Gößling-Reisemann 2014b)

Beverage type	Year	Refillable PET	One-way PET
Beer and shandy	2004	0%	4.1%
	2005	0%	4.6%
	2006	0%	6.3%
	2007	0%	6.5%
	2008	0%	7.6%
	2009	0%	6.8%
	2030 - assumption	0%	7%
Water	2004	20.3%	31.5%
	2005	21.1%	38.5%
	2006	19.3%	46.9%
	2007	18.4%	52.6%
	2008	18.7%	54.5%
	2009	18.6%	56.1%
	2030 - assumption	15%	75%
Soft drinks	2004	27.5%	33.7%
	2005	26.0%	42.2%
	2006	24.5%	47.9%
	2007	22.1%	54.3%
	2008	20.2%	59.1%
	2009	20.5%	60.5%
	2030 - assumption	15%	75%

PET bottles: fabrication, weight and sizes

PET bottles are commonly produced from PET resin by injection and blow molding (PE 2014; PlasticsEurope 2011; Kauertz et al. 2008; WRAP 2007). Losses in the manufacturing of PET are reported to be below one percent and can be assumed to be completely recycled, mostly within bottle production (Kauertz et al. 2008) and therefore do not require further consideration.

The weight per bottle differs based on the bottle design, type and size. Generally, one-way bottles have a lower specific weight (weight for packaging of 1l beverage) than refillable bottles due to lower quality requirements. Smaller bottles (e.g., 0.5l bottles) have a higher specific weight than larger bottles (e.g., 1.5l or 2l bottles). Data on PET bottle weight from several sources is summarized in Table 52. For one-way bottles the specific weights range from 20 to 50 g/l, for refillable bottles from about 41 to 71 g/l. Among the different references, only Kauertz et al. (2008) look specifically at the German market while the other studies refer to England (Oakdene Hollins 2011), Austria (Kauertz et al. 2008) and Europe (WRAP 2007); therefore the data from (Kauertz et al. 2008) is used in the analysis. Kauertz et al. (2008) does, however, not provide any information on 1l and 0.5l refillable bottles and 0.5l and 2l one-way bottles. The latter (2l one-way bottles) is calculated based on the weight ratio of 2l : 1.5l bottles provided in (Kauertz, Döhner, and Detzel 2011); for the 0.5l one way bottle the WRAP (2007) data is used as a proxy. For the 1l refillable bottle the Oakdene Hollins (2011) data

is used, and the 0.5l refillable bottle is calculated based on the weight ratio of the respective one-way bottles. The respective assumptions and data can be found at the bottom of Table 52.

Table 52: Weights of PET bottles

Reference	Bottle type	Weight [g]	Specific weight [g/1l-bottle]
Kauertz et al. 2008	1,5l one-way	35.5	23.67
	1l one-way	30.5	30.5
	1.5l refillable	62	41.33
Kauertz, Döhner, and Detzel 2011	1.5l one-way	33	22
	1.5l one-way	37.7	25.13
	2l one-way	46	23
	1.5l refillable	86	57.33
	1.5l refillable	106	70.67
Oakdene Hollins 2011	1l (refillable [58])	70	70
WRAP 2007	0.5l one-way	25	50
	0.5l "lightest bottle in Europe"	22	44
	2l one-way	42	21
author's calculations and assumptions	2l one-way	49.48	24.74
	0.5l one-way	22	44
	1l refillable	70	70
	0.5l refillable	45.90	91.80

Regarding the distribution of different bottles sizes, no data has been available for Germany. Thus, data referring to the situation in Austria (Kauertz, Döhner, and Detzel 2011) has been used and is considered to be representative for the German situation, as well. As the data refers only to one-way PET bottles, due to lack of data the same distribution has been assumed for refillable bottles –with the exception that no 2l refillable bottles are on the market for soft drinks, and the respective share has been added to 1.5l bottles. For beer, a share of 0.5l bottles of 100 % is assumed. Regarding the future development, two different scenarios are assumed, scenario A assuming constant shares and scenario B assuming a trend towards smaller bottle sizes as described by Werner (2014).

[58] It has not been indicated whether this numbers refers to one-way or returnable bottles. Considering the other data makes the bottle type "returnable bottle" rather likely.

Table 53: Shares of different bottle sizes

Beverage type	Bottle size	2012 assumption	2030 Assumption A	2030 Assumption B
Water	0.5l	7.5%	7.5%	15%
	1l	5%	5%	3%
	1.5l + 2l	87.5%	87.5%	82%
Soft drinks	0.5l	14%	14%	28%
	1l	9%	9%	7%
	1.5l (refillable)	57% (77%)	57% (77%)	46% (65%)
	2l (refillable)	20% (0%)	20% (0%)	19% (0%)
Beer and shandy	0.5l	100%	100%	100%

Specific germanium concentration in PET bottles

Based on the specific bottle weight and the specific germanium concentration in PET, the specific concentration of germanium in PET bottles can be determined. The specific concentrations for different bottles sizes and types are given in Table 54.

Table 54: Specific Ge concentration in PET bottles (own calculations)

Bottle type	Specific weight [g PET/1l-bottle]	Specific Ge concentration 27.6 mg/kg [mg Ge/1l-bottle]	Specific Ge concentration 34 mg/kg [mg Ge/1l-bottle]
0.5l one-way	44	1.10	1.36
1l one-way	30.5	0.84	1.04
1,5l one-way	23.67	0.65	0.80
2l one-way	24.74	0.68	0.84
0.5l refillable	91.80	2.53	3.12
1l refillable	70	1.93	2.38
1.5l refillable	41.33	1.14	1.41

Lifespan considerations

As described, from the product actually under study, i.e., polymerization catalysts, the germanium dissipates completely into another material flow, i.e., PET resin. With regard to the dynamic MFA study, the life span of the polymerization catalysts can be considered to be effectively zero as it is <<1. Regarding the PET bottles, it needs to be distinguished between one-way and refillable bottles. One-way bottles are usually in use for a maximum of a couple of weeks and after that are disposed of. For refillable bottles a number of 15 cycles on average is reported for Germany (Kauertz et al. 2008). Data regarding the length of one cycle have not been available for Germany and thus data referring to the situation in Austria has been used. Based on both numbers the lifespan has been calculated as shown in Table 55.

Table 55: Length and number of cycles for refillable PET bottles (Frühwirth et al. 2000 and own calculations; cf. Zimmermann and Gößling-Reisemann 2014b; Zimmermann and Gößling-Reisemann 2014a)

	Water	Soft drinks
Length per cycle (weeks)	2.9	5.0
# of cycles	15	15
Lifespan (weeks)	43.5	75

As it can be seen, the lifespan of refillable PET bottles for soft drinks is about 1.4 years while the lifespan of PET bottles for water is about 0.8 years. Still, regarding the dynamic MFA study that looks at the system in discrete steps of 1 year intervals, it is assumed that the PET placed on the market via PET bottles in year X is discarded of in the same year. This simplification does ignore the effect of overlaps (i.e. a share of bottles placed on the market in year X will be discarded in year X+1), but as the total amount of beverages annually placed on the market and so the total amount of PET bottles is considered to be constant, this assumption only leads to very minor deviations, basically resulting from the change in the shares of one-way/refillable over time.

Material flows into use phase

As described above, the absolute germanium flows are calculated based on the specific germanium concentration in PET bottles, the beverage consumption and the share of different bottles types and sizes. Due to data uncertainties, various assumptions had to be made and scenarios needed to be defined as described in the previous section. Based on these, a min and a max scenario are defined to provide an idea of the range in which the absolute germanium flows are located.

Table 56: Assumptions for Min and Max Scenario of germanium flows into use

	Min scenario	Max scenario
Share of GeO_2 catalysts in production	5%	10%
Germanium concentration in PET	27.6 mg/kg	34 mg/kg
Beverage consumption	Mean minus 10%	Mean plus 10%
Shares of bottles types	as given in Table 51	as given in Table 51
Specific bottle weight	as given in Table 52	as given in Table 52
Shares of different bottle sizes	Assumption A from Table 53	Assumption B from Table 53

Based on these parameters, the calculation of germanium flows is straight-forward for one-way bottles. For refillable bottles, the number of cycles needs to be taken into account, i.e., one (1l) refillable bottle stores the fifteen fold amount of beverages.

The results show a steady increase of the germanium flows into use as shown in Figure 28. In the min-scenario the annual flows of germanium into the use phase of polymerization catalysts and PET bottles, respectively, increases from about 235 kg in 2012 to 284 kg in 2030. In the max-scenario the annual flows increase from 707 kg in 2012 to 908 kg in 2030.

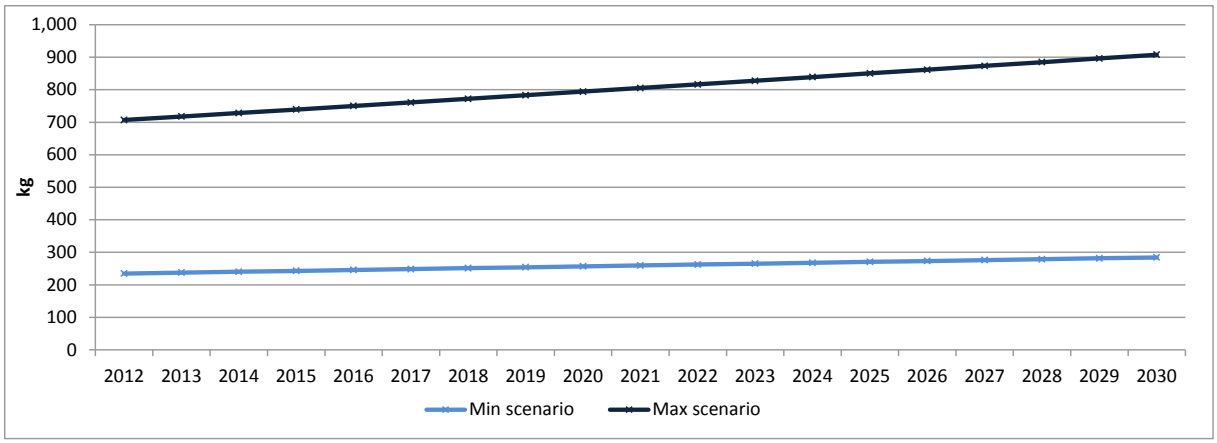


Figure 28: Germanium flows into use

In both scenarios, this increase is caused by the growing total share of PET as bottle material and particularly by the growing share of one-way PET bottles which are less resource efficient than refillable bottles.

Dissipation in use phase of PET bottles

The use phase of PET bottles mainly consists of storage time. Depending on the length of the storage time, environmental conditions and beverage specific factors (pH, carbonization etc.), some dissipation of catalyst material from the PET into the beverage will occur. The issue of contamination of beverages from the bottle material is rather well documented for antimony due to its toxicity (see for example Bach et al. 2012; Reimann, Birke, and Filzmoser 2010; Reimann and Birke 2010; Krachler and Shotyk 2009; Westerhoff et al. 2008). Reimann, Birke, and Filzmoser (2010), for example, found antimony concentrations in bottled water that were 21 times higher when sold in PET bottles compared to glass bottles[59], however still well below drinking water guidelines (in Germany 5 µg/l; Westerhoff et al. 2008) . Germanium concentrations in bottled water analyzed by Westerhoff et al. (2008) in general were relatively low (0.015 µg/l as median of bottle waters from 28 countries across the globe). While for most countries values well below 1 µg/l could be found, significantly higher values could be found, though, in French bottled water (12 µg/l), German bottled water (3 µg/l) and four out of eleven Japanese waters (1.1 µg/l to 8.9 µg/l) (Westerhoff et al. 2008). In the study by Reimann, Birke, and Filzmoser (2010) that was based on 77 waters from Germany and 49 from the rest of Europe, however, no increased germanium concentrations have been found (concentrations below 0.02 µg/l) and also in a more recent study by Reimann, Birke, and Filzmoser (2012) no increased germanium values have been found in water from PET bottles. In another rather extensive survey (Reimann and Birke 2010) the average low concentration of germanium is confirmed, but at the same time a significant spread of germanium concentrations with values in single bottled waters well above 3 µg/l is documented. Here, these values are mainly explained by anomalies of single wells and only to a very limited extent by bottle leaching (Reimann and Birke 2010). Still, a test particularly on

[59] In glass bottles on the other hand, significantly higher contaminations with cerium and lead were found.

leaching of germanium from bottles into beverages did return a value of 1.4 µg/l (total amount of leaching losses during use phase) (Reimann and Birke 2010).

Based on this, it can be said that leaching of germanium from PET bottles is principally possible but data on the exact dissipation rates is scarce. This uncertainty is dealt with in the model by analyzing a range of zero dissipation up to 1.4 µg/l as indicated by the results from Reimann and Birke (2010), who conducted the only study looking at leaching of germanium from PET bottles. With regard to the specific germanium content in PET bottles, these losses correspond to a relative loss of germanium in the use phase of PET bottles of 0.04 % to 0.22 %. Based on this, the scenarios shown in Table 57 are analyzed in the model.

Table 57: Germanium losses (leaching) during use phase of PET bottles

		2012/2030 Min	2012/2030 Mean	2012/2030 Max
Dissipative losses from use phase of PET bottles	$L_{Use,PET}$	0%	0.11%	0.22%
- **to the environment**	$L_{Use,PET,env}$	0%	0.11%	0.22%

5.3.4 End-of-life of PET Bottles

While GeO_2 polymerization catalysts dissipate completely into the PET resin, and thus total losses in the use phase occur, and no end-of-life for polymerization catalysts in terms of the explanations given in section 4 exists, the EOL of PET bottles can be looked at to identify the further fate of the dissipated material. A recovery of germanium (or other catalysts materials) from EOL PET is currently neither practiced nor feasible (Roewer 2014; Oakdene Hollins 2011). In fact, according to expert information, recycling of catalysts material such as antimony from EOL PET would destroy the polymers and render PET recycling impossible (M. Neal, pers. comm.). The end-of-life practices for PET bottles are described in the following.

The deposit system for the collection of EOL PET bottles in Germany is quite efficient and only minimal losses (max. 5 % to 7 %) occur (Welle 2011; Kauertz et al. 2008). In 2009, for example, the collection rate was 93.5 % in Germany compared to 48.4 % on the average in Europe (Welle 2011). Based on this, collection losses of 5 %, 6 %, and 7 % are assessed in the model. Regarding the not-collected bottles treatment with household waste, i.e., incineration can be assumed. Ashes and slags from incineration of household waste are either landfilled (10 % according to Faulstich et al. 2010) or used for construction purposes (as filling material; about 90 % according to Faulstich et al. 2010), e.g. in road construction, i.e., the embedded germanium content enters another material flow.

A significant share of the collected EOL PET bottles is recycled in a closed-loop[60], i.e. is used as input material in the fabrication of new PET bottles (Kauertz et al. 2008). Principally, bottle-to-bottle recycling is more expensive and technologically challenging than recycling for use in non-food products, but more efficient collection systems reducing the contaminations in the waste stream, significant technological advances over the past ten years (development of the "super-clean-recycling-process") as well as a demand from beverage companies for more sustainable PET bottles (through an improved EOL management) for marketing reasons increased the share of bottle-to-bottle recycling significantly (Welle 2011). However, no accurate data on the share of PET bottles used for bottle-to-bottle recycling for Germany is available. Regarding Europe, it can be assumed that about half of the collected bottles is used as secondary input material for the production of PET bottles and other food packaging applications (Welle 2013). As Germany has by far the highest capacity for bottle-to-bottle recycling (Welle 2010), an even higher share of bottle-to-bottle-recycling can be assumed for Germany (>60 %). Based on this, two scenarios –60 % and 70 % closed-loop recycling– are analyzed in the model.

The rest of the PET recyclates is either recycled in an open-loop, incinerated or landfilled. For Germany, however, it can be assumed that the main share will be recycled due to the well working deposit system for collection or incinerated, while landfilling is an exception (and also banned in Germany) (Shen and Worrell 2014). Regarding plastics in their entirety, a collection rate of 92 % to 98 % is reported for Germany by Shen and Worrell (2014), while only 30 % to 37 % are actually recycled, and the rest is incinerated with energy recovery[61]. Based on this, open-loop recycling rates of 30 % and 37 % are analyzed in the model. The quota of recycled plastic waste appears to be higher in countries without energy recovery system for incinerated waste such as Lithuania or Malta (Shen and Worrell 2014). Assuming that about 60 % of PET recyclates from bottle recycling are recycled in a closed-loop and applying the mentioned quotas to the rest leaves about 12 % to 14.8 % for open-loop recycling and 25.2 % to 28 % for incineration. Regarding incineration the same uses of incineration residues as described before are assumed (10 % landfilling, 90 % other material flows).

Within open-loop recycling of PET, the fiber market currently appears to be the biggest outlet with a share of about 50 % in 2009 (Welle 2011). Here, recovered PET is used in a variety of applications like padding to stuff anoraks, sleeping bags and soft toys, fleece fabric for sweatshirt, jackets and scarves, geotextiles, non-woven fabrics used in backpacks, car carpets etc. (European Commission 2008). Other potential applications include sheets, strappings, and non-food packaging (Welle 2011).

Table 58 summarizes the parameter settings for the different PET bottle EOL scenarios while Figure 29 shows the material flows at EOL of PET bottles for the baseline scenario referring to the input to EOL stage (=100 %).

[60] The steps of mechanical plastic recycling (sorting, shredding, washing and drying, melting and reprocessing) are described in detail in (Shen and Worrell 2014), the specifics of bottle-to-bottle recycling are described in (Welle 2011).

[61] In comparison, on EU level about 50% are recycled and the rest incinerated or landfilled (M. Neal, pers. comm.).

Table 58: EOL parameters for PET bottles

EOL parameter	Scenario & Year		
EOL-collection	**A**	**B**	**C**
- **EOL-collection losses**	5%	6%	7%
Closed-loop recycling	**2012/2030 A**		**2012/2030 B**
- **Closed-loop recycling rate**	60%		70%
Open-loop recycling/ incineration	**A**		**B**
- **Share to open-loop recycling (dissipation to other material flows)/ incineration**	30%/70%		37%/63%
- **Incineration residues to landfills/ other material flows**	10/90%		

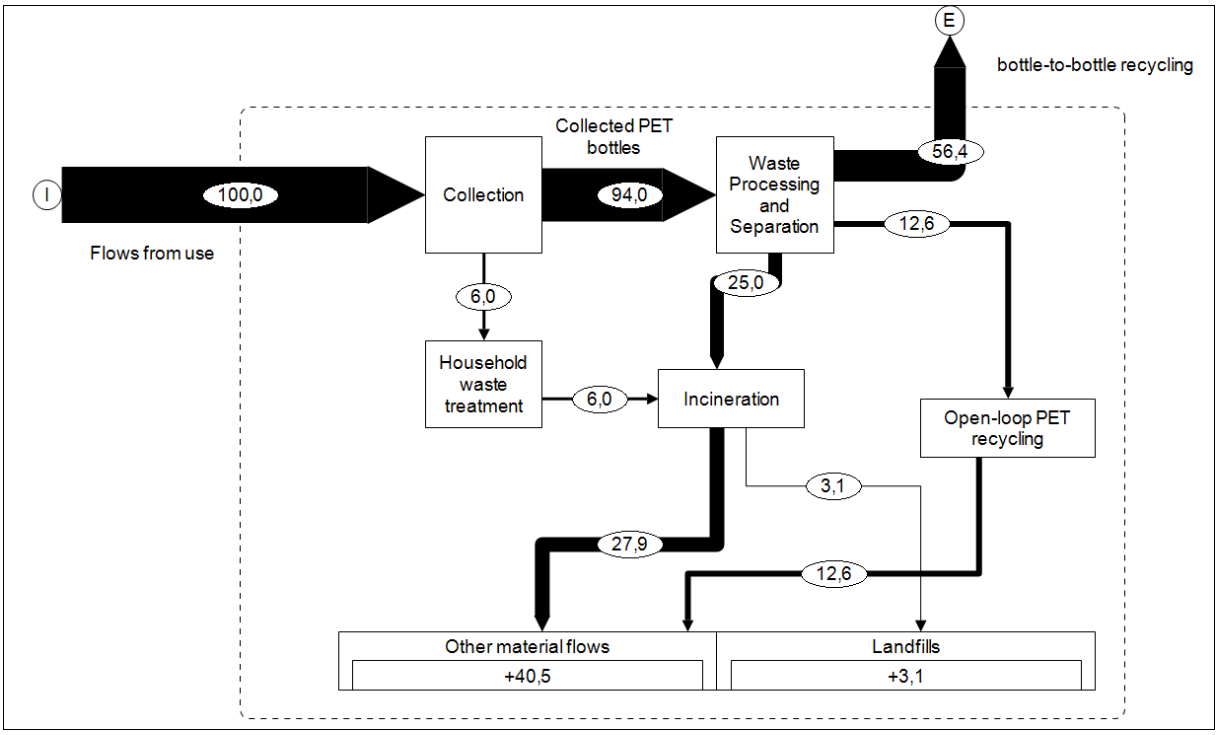


Figure 29: Material flows at EOL of PET bottles (all flows in relation to input flow from use phase (=100%))

5.3.5 Results: Material Flows along the Life Cycle

Based on the descriptions given regarding each life cycle stage, the germanium flows along the life cycle of polymerization catalysts and additionally of PET bottles have been analyzed for different scenarios following the approach described in chapter 4.

The different assumptions regarding the parameters determining the relative dissipative material losses are summarized in Table 59, the relevant parameter setting for the min and max scenarios for the absolute material flows have been summarized in Table 56. The results for the baseline scenario as well as main points from the assessment of the alternative scenarios are described in the following. The full results for all analyzed scenarios including all major material flows, in-use stock, and cumulative dissipative losses to different media are given in Appendix B) in Table A 49 to Table A 64.

Table 59: Summary of analyzed scenarios along the life cycle of polymerization catalysts and PET bottles. Shading indicates the parameter setting of the baseline scenario.

Life cycle stage	Parameter	Scenario & Year			
		2012 A	**2012 B**	**2030 A**	**2030 B**
Material production	$L_{MP,Ge,lf}$	15%	90%	10%	90%
Fabrication & manufacturing	L_{FM}	0%		0%	
Use Phase	L_{Use}	100%		100%	
- **losses to other material flow**	$L_{Use,omf}$	100%		100%	
PET: Use phase		**2012/2030 Min**	**2012/2030 Mean**	**2012/2030 Max**	
- **losses to environment**	$L_{Use,PET,env}$	0%	0.11%	0.22%	
PET End-of-life		**2012/2030 Min**	**2012/2030 Mean**	**2012/2030 Max**	
- **aggregated total losses**	$L_{EOL,PET,lf}$	3.04%	3.1%	3.1%	
	$L_{EOL,PET,omf}$	38.55%	40.5%	42.5%	
	$R_{EOL-PET}$		60%	70%	
PET EOL - disaggregated					
EOL bottle collection		**A**	**B**	**C**	
- **Collection losses**		5%	6%	7%	
Closed-loop recycling		**2012/2030 A**		**2012/2030 B**	
- **Closed-loop recycling rate**		60%		70%	
Open-loop recycling/ incineration		**A**		**B**	
- **Share to open-loop recycling (dissipation to other material flows)/ incineration**		30%/70%		37%/63%	
- **Incineration residues to landfills/ other material flows**		10/90%			

Baseline scenario

The results show a complete dissipation of germanium along the product life cycle. Figure 30 visualizes the material flows for selected years. In the baseline scenario, in material production a fraction of 15 % of the input material dissipates in 2012 and further decreases to 10 % in 2030. In the use phase, the germanium dissipates completely into the PET. Afterwards, there is further dissipation particularly at the EOL of PET bottles –mainly into other material flows (79 % in 2012, 84 % in 2030) but also to landfills (about 6 %). A share of the EOL PET is recycled in a closed-loop along with the embedded dissipated germanium. In-use dissipation, i.e., leaching of germanium into the beverage, does not occur on a relevant scale. Other material flows –comprising recycled PET in open-loop recycling as well as the use of incineration residues as construction material etc.– are the dominating receiving medium with a share in annual dissipation of 79 % to 84 %. Landfills account for 16 % to 21 %.

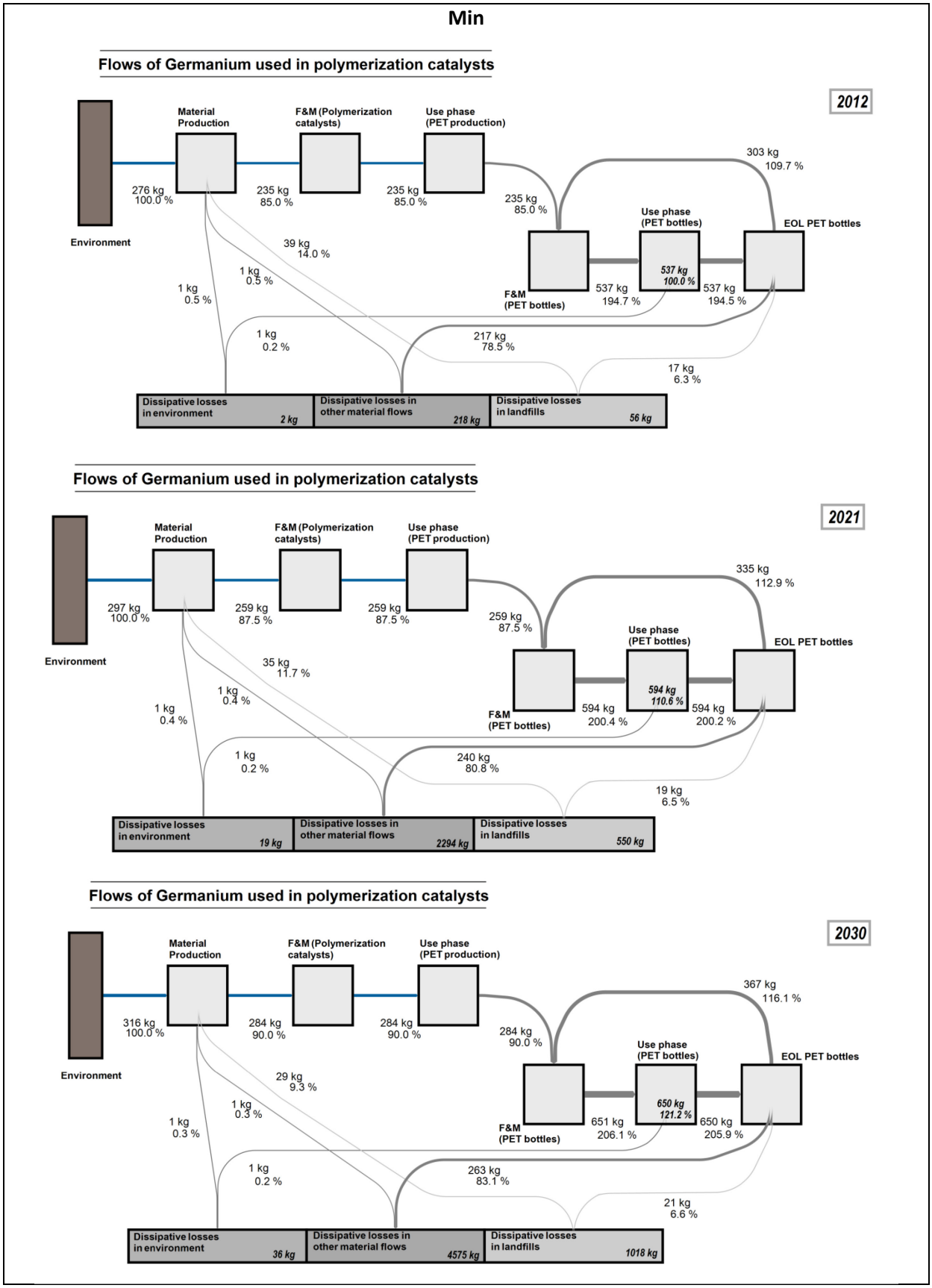


Figure 30: Material stocks and flows in selected years in polymerization catalyst baseline scenario; relative material flows refer to input flow from environment (=100%), relative in-use stocks refer to 2012 in-use stock (=100%); percentages may not add up to 100% due to rounding differences.

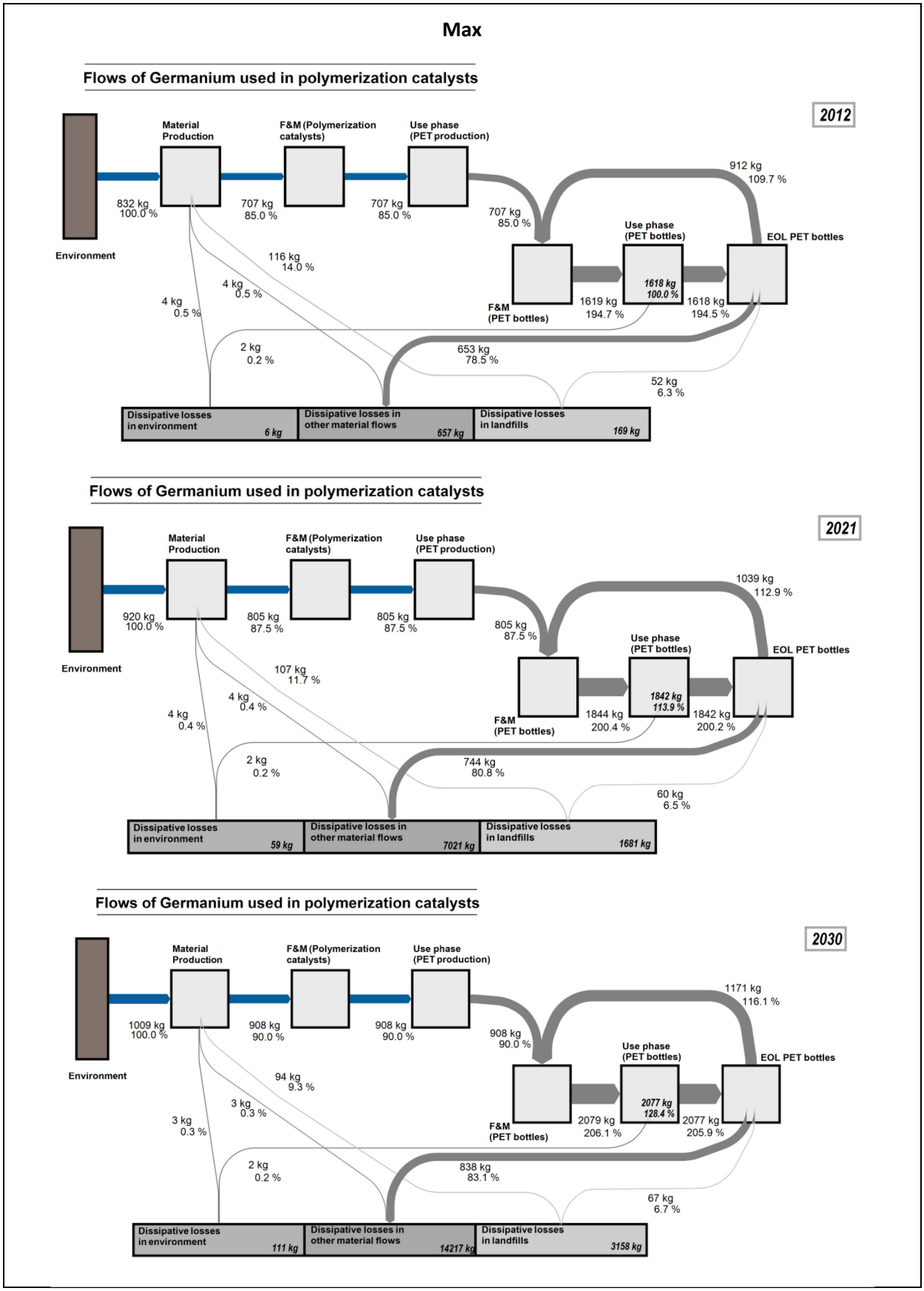


Figure 30 continued.

The total dissipating amount of germanium is 276 to 832 kg in 2012 and increases to 316 to 1,009 kg in 2030. In the considered timeframe a total of 5,629 to 17,487 kg of germanium dissipates. The annual material demand (input to F&M stage) increases from 235 to 707 kg in 2012 to 284 to 908 kg in 2030.

Variations of material production stage

The alternative material production scenario (scenario B) which extends the defined system boundaries by including losses in material production not strictly related to the analyzed product shows significantly higher material losses in the material production stage. This emphasizes the amount of germanium actually extracted from the environment in the production of carrier metals such as zinc, while downstream processes –i.e., all processes after material production– and their input and outputs remain unaltered. Figure 31 visualizes the resulting changes. Dissipation from material production is considerably increased.

The dissipative losses from material production amount to 2,111 to 6,346 kg in 2012 (compared to 41 to 125 kg in the baseline scenario), and increase to 2,558 to 8,170 kg in 2030 (compared to 32 to 101 kg in the baseline scenario). Accordingly, the CDL in 2030 are increased, to 49,290 kg to 153,158 kg compared to 5,629 kg to 17,486 kg in the baseline scenario.

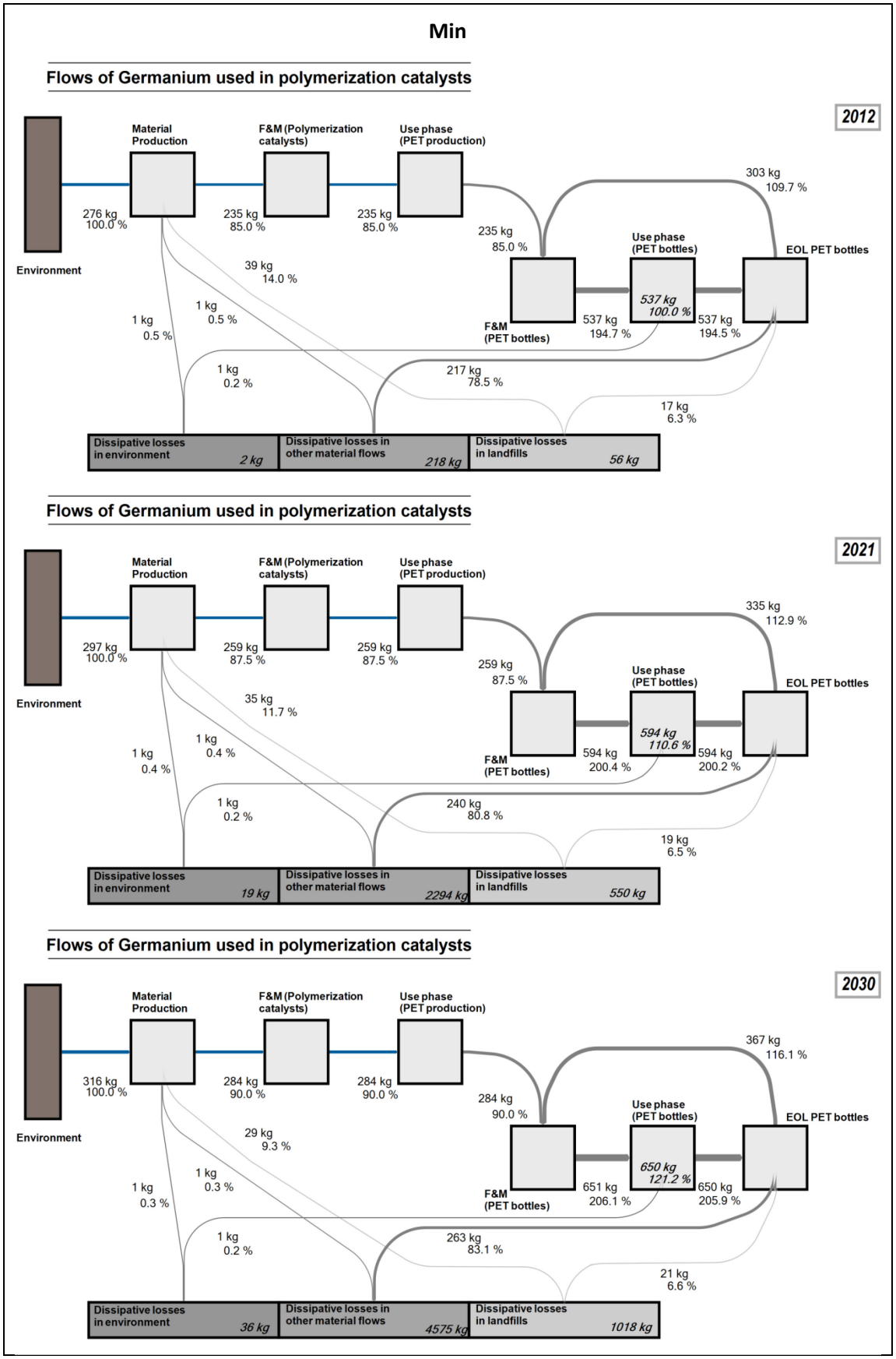


Figure 31: Material stocks and flows in selected years in alternative germanium material production scenario – with expanded system boundaries; relative material flows refer to input flow from environment (=100%), relative in-use stocks refer to 2012 in-use stock (=100%); percentages may not add up to 100% due to rounding differences.

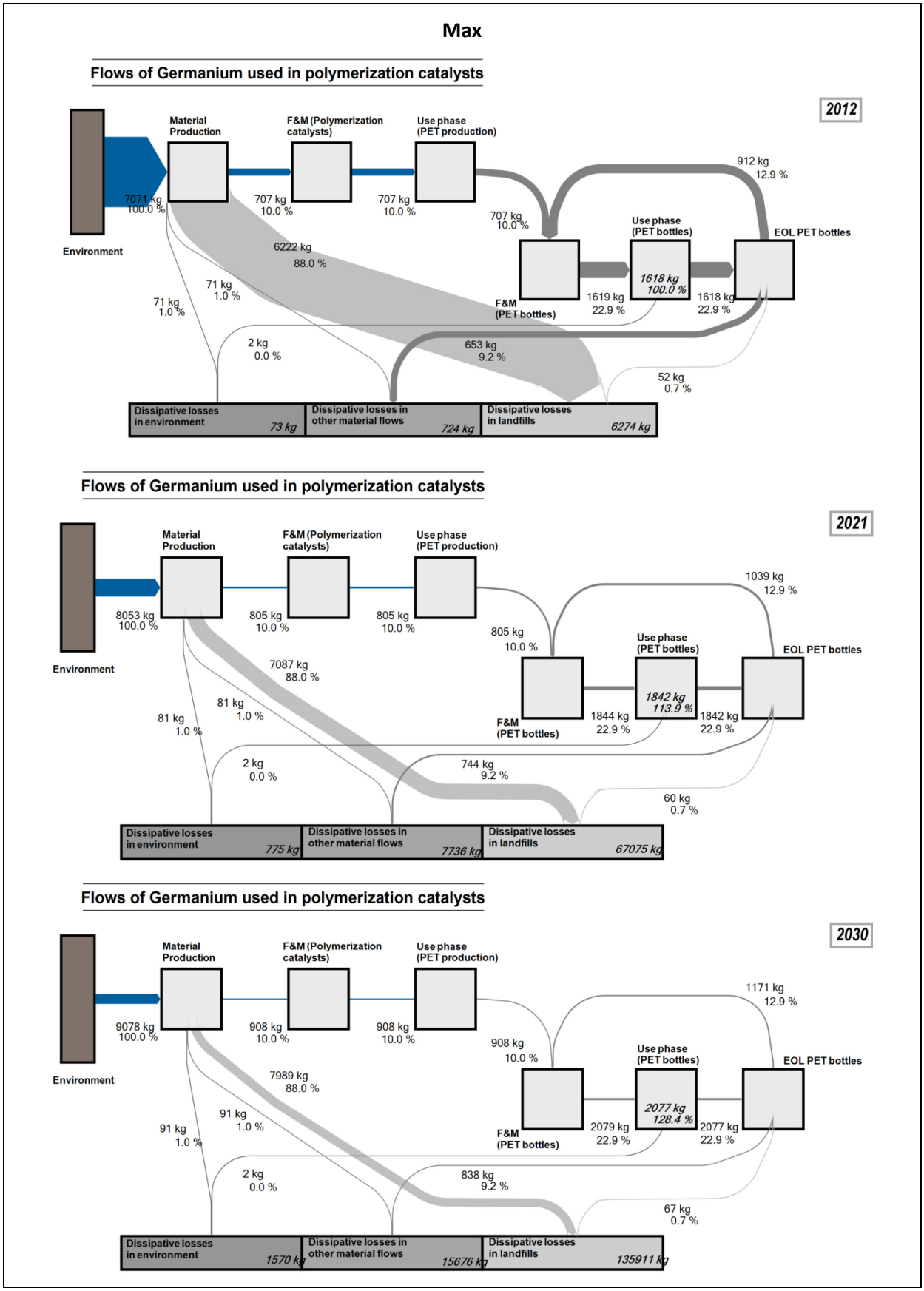


Figure 31 continued.

Variations in the use phase of PET bottles

In the use phase, the in-use dissipation of germanium (i.e., leaching of germanium from the PET bottles into the beverage) has been varied based on the data range found in literature. Even in the scenario with the highest leaching rates found in literature, in-use dissipation does not exceed 5 kg/a and can be considered insignificant in comparison to other dissipative flows in the polymerization catalysts and PET bottle life cycle.

Variations in EOL

In the EOL stage different parameters have been varied. The first parameter is the collection losses which have been varied according to the range found in literature. The variations result in minor increases or decreases, respectively, of EOL-dissipation and closed-loop recycling as well as material demand. The assumed reduction of collection losses from 6 % to 5 %, for example, results in a reduction of EOL-dissipation from 284 to 905 kg in the baseline scenario to 280 to 893 kg in the alternative scenario.

The second EOL parameter that has been varied was the closed-loop recycling share which has been increased to 70%. This increase in bottle-to-bottle (B2B) recycling decreases material demand and dissipative losses by over 20% as visualized in Figure 32. The analyzed system shows a high sensitivity regarding changes of the B2B-recycling rate. For example, changes of the B2B-recycling rate result in changes of the annual dissipative losses by a factor of about -2.15. E.g., a change of B2B recycling of -10 % (compared to the baseline scenario), results in an increase of dissipation by 21.3 %. The same factor applies to changes of material demand.

The third parameter that has been varied regarding the EOL stage is the share of material in open-loop recycling that goes to incineration and actual recycling, respectively. This parameter variation results only in a minor shift in the distribution of dissipative losses to other material flows and landfills. In the min scenario, about 1.5 to 1.7 kg per year dissipate to other material flows instead of landfills; in the max scenario, 4.2 to 5.5 kg dissipate to other material flows instead of landfills. In relative terms, this means an increase of the cumulative dissipation to landfills by 3 % in 2030, while the cumulative dissipation to other material flows is reduced by 0.6 %.

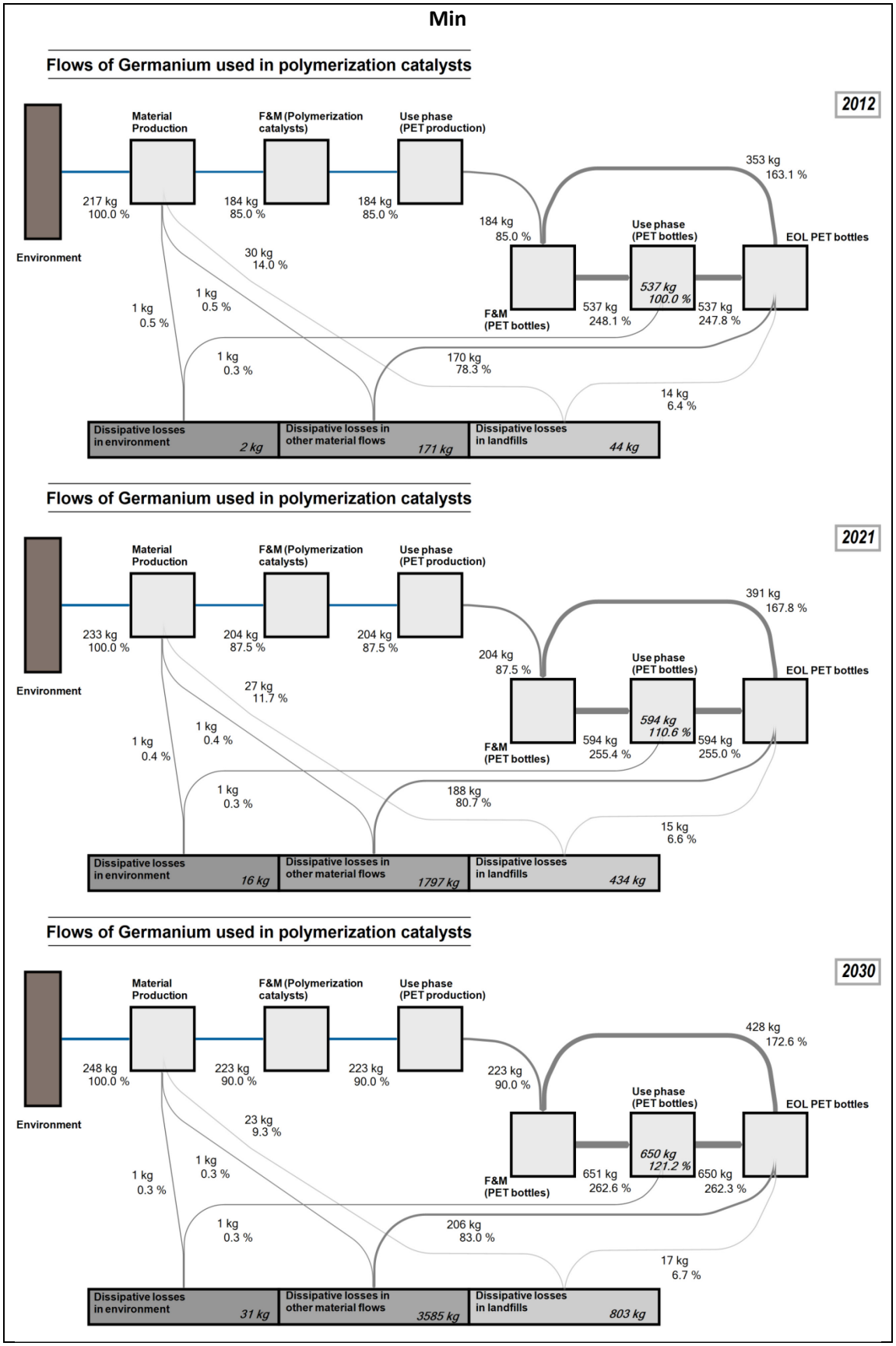


Figure 32: Material stocks and flows in selected years in alternative EOL scenario with increased closed-loop recycling share; relative material flows refer to input flow from environment (=100%), relative in-use stocks refer to 2012 in-use stock (=100%); percentages may not add up to 100% due to rounding differences.

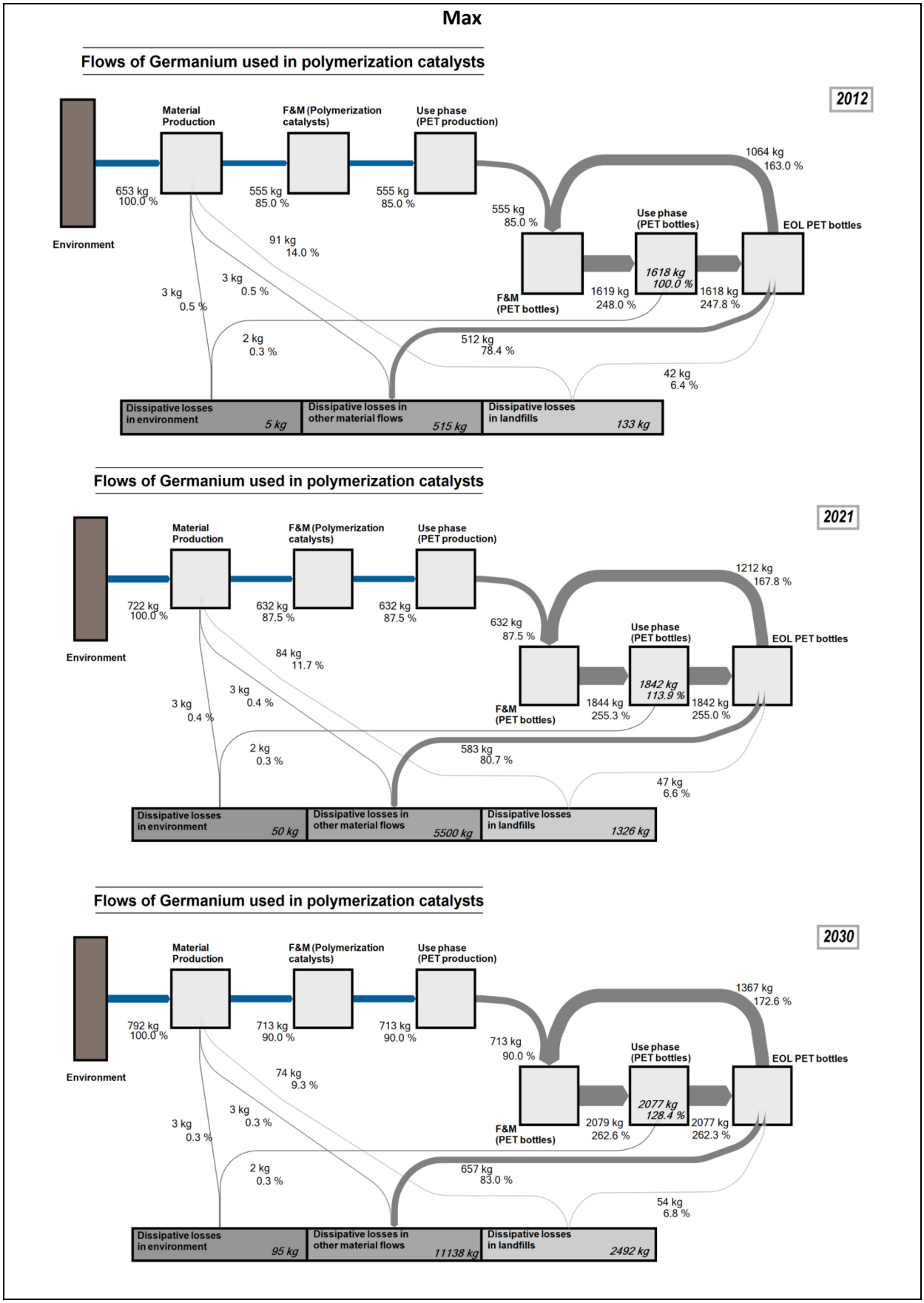


Figure 32 continued.

Summary

The CDL for the considered time span from 2012 to 2030 are summarized in Table 60 for the different analyzed scenarios. The highest reductions of dissipation are achieved by the increased B2B-recycling rate. The alternative scenario for the material production stage in which the system boundaries have been expanded to include germanium losses not strictly related to the analyzed products shows substantial increases of CDL. The other scenarios show comparably low variations of the cumulative dissipative losses of up to 1.4 %.

Table 60: Summary of cumulative dissipative losses in different polymerization catalyst scenarios

		Cumulative dissipative losses [kg]		Change from baseline scenario	
		Min	Max	Min	Max
Baseline scenario		5,629	17,486	-	-
Material production	**Scenario B**	49,290	153,158	775.6%	775.9%
PET-use phase	**Min**	5,621	17,508	-0.1%	0.1%
	Max	5,637	17,511	0.1%	0.1%
PET- EOL collection	**Scenario A**	5,553	17,256	-1.4%	-1.3%
	Scenario C	5,706	17,726	1.4%	1.4%
PET EOL – closed loop recycling	**Scenario B**	4,419	13,726	-21.5%	-21.5%
PET EOL – open-loop recycling	**Scenario B**	5,629	17,486	0.0%	0.0%

5.3.6 Conclusions & Discussion

Germanium used in polymerization catalysts dissipates completely in another material flow, i.e., into PET. As the receiving material flow has a rather short turn-over time (<<1 year) and further dissipation occurs within a rather short timeframe, analyzing the further life cycle of the subsequent product provides valuable information regarding the further fate of the dissipated germanium. Also within this expanded life cycle there is no recovery of the germanium which has dissipated into the PET. A significant share of the carrier material (i.e., the PET) is recycled in closed-loop along with the embedded germanium, though. Still, germanium used in polymerization catalysts which dissipates into PET has to be considered lost for future use in other germanium applications.

The material production stage of germanium and germanium dioxide, respectively, is rather efficient within the process routes of germanium recovery. Expanding the system boundaries to include process routes that produce zinc without recovering germanium as a by-product, however, changes the picture significantly, as over 90 % of the germanium contained in ores dissipates in the material production stage. In absolute terms, these dissipative losses amount to 2 to 6 Mg in 2012, which is a multiple of the actual material demand for polymerization catalysts which ranges from 235 kg to 908 kg. Even compared to the total consumption of germanium in Germany (22,500 kg to 37,500 kg in 2012, cf. section 5.1.3) the scale of the dissipative losses from material production appears considerable. As the material production stage is not product specific these conclusions are valid for ger-

manium in general and make another point very clear. Even though germanium is among those materials most frequently considered to be of highest criticality, there is an enormous potential for improvement in material production. If losses from the processing of other Ge bearing ores or coal (ashes) could be included (which was not possible due to lack of reliable data), the losses would be even higher, emphasizing the potential for improvements even more.

In the use phase of polymerization catalysts, there is a complete dissipation and no indications for future changes could be found. Still, there are some uncertainties regarding the share of GeO_2 catalysts in the production of bottle grade PET. Accurate data regarding the situation in Europe and Germany has not been available and an estimation (5 to 10 %) has been cross-checked with the CPME and found to be reasonable. However, –if available– more accurate data would allow for a refinement of the model.

In the PET life cycle, a simplified approach has been used regarding the consideration of the lifespans of PET bottles, assuming an "instant" disposal of the PET bottles as described in section 5.3.3/Lifespan considerations. As described, this simplification has only a minor influence on the results –especially compared to the other uncertainties determining the difference between min and max scenario– and does not call for a refinement. Although beverage consumption is assumed to remain constant, in-use stock as well as material demand and resulting dissipation increase over time. This increase is caused by the trend to use one-way bottles instead of refillable bottles as well as by the trend to use smaller bottle sizes. Accordingly, an increase in the use of refillable bottles instead of one-way bottles could contribute to reducing dissipation and material demand considerably. Refillable bottles are significantly more resource efficient (every refillable bottle transports roughly a fifteen-fold amount of beverage before being recycled) and increasing the share of refillable bottles would result in significant changes in the material flows in the upstream processes.

At EOL, germanium recovery appears to be unfeasible as a recovery of the catalyst material would destroy the polymers and render the PET recycling unfeasible. Plastic recycling is, however, an important element of any strategy to reduce environmental problems associated with plastic waste, including issues such as resource consumption and greenhouse gas emissions (see, e.g., Shen and Worrell 2014; Welle 2011) as well as accumulation of plastic waste in oceans (see, e.g., Gross 2013; Andrady 2011; Kershaw et al. 2011). Future changes regarding a recovery of catalyst material are not indicated and would require a solution that allows both, PET recycling and recovery of catalyst material. Besides closed- and open-loop recycling, a share of EOL PET is incinerated with energy recovery as there are high economic incentives for this in Germany. Also this EOL option further reduces the feasibility of germanium recovery as the already low concentrated germanium is further diluted. Thus, germanium dissipated into PET must be considered to be lost for future use in any germanium application. Regarding open-loop recycling, even the theoretical possibility of recovery hardly exists as further dilution occur as well as use in unknown applications. Still, the analysis shows the large potential influence of increasing closed-loop recycling rates to material demand and dissipation which can be reduced significantly.

Even though material already dissipated into PET still needs to be considered lost, the decline in demand for “new” PET by increasing B2B recycling reduces dissipation in the upstream life cycle stages, particularly in material production, as well as further dissipation from PET EOL. Changes of the B2B recycling rate by 1 % result in reductions of dissipative losses in upstream processes by 2.15 %. In the analyzed scenario in which an increase of B2B recycling from 60 % to 70 % has been analyzed, accordingly, a reduction of dissipative losses and material demand by over 21 % could be observed. The CDL are reduced by 1,210 kg to 3,760 kg corresponding to 0.8 % to 2.5 % of the 2012 world production. These improvements apply not exclusively to germanium but also to other polymerization catalyst material such as titanium and antimony. Thus, increasing B2B recycling can be considered an effective measure to reduce dissipation of various materials, particularly when considering that the required infrastructure already exists and the economic feasibility has been proven.

Some uncertainties exist regarding the use of residues from the incineration of EOL PET, and the assumed shares (10 % landfilling, 90 % other material flows) might differ from the actual situation.

Many of the parameters used in the analysis are rather country specific, and the general problem of germanium dissipation from use in polymerization catalysts is slightly more relevant for Germany than for other countries, as the share of PET packaging in Germany is twice as high as globally (about 60 % compared to 30 %) (Werner 2014). Still, the general issues will be the same in all countries as germanium recovery from PET is practiced nowhere. Besides the absolute size of material flows, the main differences will be on the treatment of EOL PET, i.e., in the share for closed- and open-loop recycling, and incineration.

As a last point, it has to be noted that the data on the share of germanium catalysts in bottle-grade PET production is rather insufficient. As a result, there is a factor of two in the absolute results between min and max scenario. This uncertainty needs to be taken into account for further interpretations of the absolute results.

5.4 Thermal Barrier Coatings in Aircraft Engines

Thermal barrier coatings (TBC) are used in turbines –stationary gas turbines as well as aircraft engines– to isolate turbine components from the hot gas stream (cf. Zimmermann and Gößling-Reisemann 2014a). In stationary gas turbines and aircraft engines, efficiency and core power directly relate to the gas temperature entering the turbine section (Clarke, Oechsner, and Padture 2012). Operating temperatures can go up to 1,400°C which is why turbine components such as blades, vanes, and combustor are coated with a ceramic thermal barrier coating (Clarke, Oechsner, and Padture 2012; Vaßen et al. 2010; Schweda 2010; Batista 2007).

In the following, the focus is on coatings used in aircraft engines which –in terms of quantity– dominate the TBC market. They account for about 65 % while stationary gas turbines account for the balance (Clarke, Oechsner, and Padture 2012). The results are, however, to some extent transferable to stationary gas turbines as described in section 5.4.6 (Conclusions & Discussion). For both fields of application a steady growth in the coming decades is forecast (Clarke, Oechsner, and Padture 2012).

Commonly (market share of at least 90 %), yttria (Y_2O_3)-stabilized zirconia (YSZ) is used for turbine coatings (J. Sopka, pers. comm.; Zimmermann and Gößling-Reisemann 2014b; Clarke, Oechsner, and Padture 2012; Subanovic 2009). YSZ is chosen because of its low, temperature invariant thermal conductivity (Evans, Clarke, and Levi 2008). Increasing the efficiency of gas-turbine engines has always been object to research but the introduction of TBCs has proven to be a major step in this endeavor, allowing significantly increased engine temperatures hereby increasing efficiency. The coated parts include stationary guide vanes, rotating blades, shrouds in the high-pressure section, and the combustor surface. For determining the absolute material flows, engines of short-, mid-, and long-distance aircrafts need to be distinguished.

5.4.1 Material Production Stage: Rare earths / Yttrium

Quite generally, the production of REE (pure metals) can be divided into the following steps: extraction, beneficiation, hydrometallurgy, and separation. For the ion-adsorption clays from South China the steps of beneficiation and hydrometallurgy can be omitted as they go directly into the separation processes (Kennedy 2014; Wall 2014). Thus, as yttrium is almost exclusively produced from ion-adsorption clays, the relevant process steps are extraction and separation while the process steps of beneficiation (includes crushing, grinding, flotation, and filter pressing to produce a mixed REE concentrate, Du and Graedel 2011c) and hydrometallurgy are not relevant for further consideration.

Separation of REE is commonly performed by the solvent-extraction (SX) process. The separation is conducted in various process steps and requires a high amount of chemical agents (Kennedy 2014) such as ammonium sulfate or EDTA (ethylenediaminetetraacetic acid) (Wall 2014; Bao and Zhao 2008). The steps of separation through SX are shown in Figure 33.

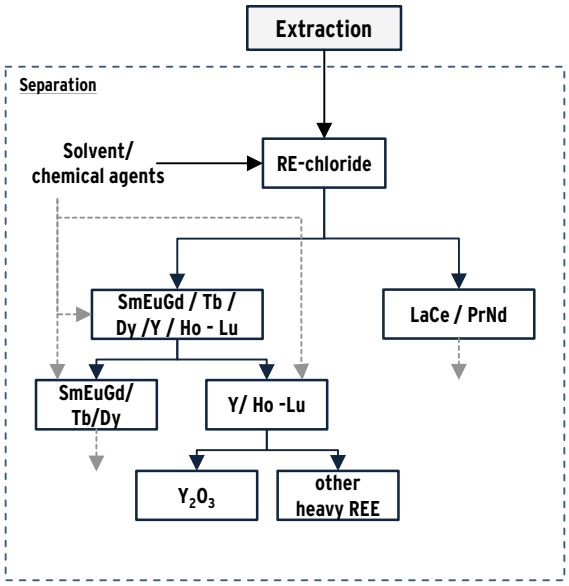


Figure 33: Process steps of RE separation through solvent extraction (adapted from Kennedy 2014 with additional information from Wall 2014; Bao and Zhao 2008)

Information on process efficiencies is hardly available. Du and Graedel (2011c), however, performed a first assessment of the cycles of selected REE including yttrium, based on published and unpublished data from the U.S., China, and Japan. The flows along the life cycle stages of material production (comprising mining and separation) and fabrication and manufacturing are summarized in Table 61. The total losses from the material production stage amount to about 28 % reffering to the input into material production.

Table 61: Global yttrium flows and relevant losses from mining to fabrication and manufacturing in 2007 (adapted from Du and Graedel 2011c)

Life cycle stage	Material production					Fabrication and manufacturing
	Mining			Separation		
	Mined as ore	Losses (tailings)	Output	Losses (slags)	Output (REO)	Losses
Y flows in Gg	17.4	3.5	13.9	1.4	12.5	1.9
Relative losses (in relation to input to process stage)		20%		10%		15.2%

According to the explanations given by Du and Graedel (2011c) –although not noted explicitly– , it can be assumed that this number (28 % losses in material production resulting from 20 % losses in mining and 10 % in separation) is an average of all major process routes of yttrium recovery. Still, it is not entirely clear in how far yttrium recovery from REE sources with comparably low yttrium contents such as bastnäsite or monazite with probable lower recovery efficiencies (the additional process steps of beneficiation[62] and smelting mean additional losses) have been considered, and the

[62] For beneficiation efficiencies between 80 and 85% are reported for operations in China (Jordens, Cheng, and Waters 2013).

indicated losses of 28 % seem rather optimistic. Additional reliable data could not be found, though. Against this background, the losses reported by Du and Graedel (2011c) are used for the base year 2012 in scenario A as well as in an optimistic scenario B, while in an alternative pessimistic scenario C a higher value of 50 % is analyzed. Scenario C –although based on rather rough assumption– can be assumed to include such process routes that process input material with much lower yttrium concentrations (e.g., bastnäsite, loparite, monazite; cf. section 5.1.4, Table 29) and have much lower recovery efficiencies regarding yttrium or no recovery of yttrium at all. It therefore corresponds to the alternative scenarios that have been analyzed regarding the material production stage of indium, gallium, and germanium, in which the defined system boundaries have been expanded. It needs to be considered, though, that this scenario is based on rather rough estimations as no data on the recovery of yttrium from sources with lower yttrium concentrations could be obtained.

Regarding the future development of recovery efficiencies, no reliable information could be found at all. Against this background, constant losses are assumed in the scenario C, an improvement of recovery efficiency of 10 % is assumed in the scenario A and an improvement of 20 % is assumed in the scenario B. Based on the little available information it is assumed that these losses almost exclusively end up on landfills. The losses and their distribution to the different receiving media are summarized in Table 62.

Table 62: Yttrium losses from material production stage

		2012 C	2012 A	2012 B	2030 C	2030 A	2030 B
Dissipative losses from yttrium production	L_{MP}	50%	28.0%	28.0%	50%	21%	13.84%
- **to the environment**	$L_{MP,env}$	0.5%	0.3%	0.3%	0.5%	0.2%	0.1%
- **to other material flows**	$L_{MP,omf}$	0.5%	0.3%	0.3%	0.5%	0.2%	0.1%
- **to landfills**	$L_{MP,lf}$	49%	27.4%	27.4%	49%	20.6%	13.64%

5.4.2 Fabrication & Manufacturing

The stage of fabrication and manufacturing comprises the production of YSZ powder and its application to the engine parts.

Spray powder production

Various ways of producing YSZ powder are described in literature (e.g., Biswas et al. 2011; Minfang et al. 2005; Boaro, Vohs, and Gorte 2003; Khollam et al. 2001; Yuan et al. 1998), some referring to YSZ production for other applications (e.g., solid oxide fuel cells). In most process routes, Y_2O_3 powder is solubilized using nitric acid and added to Zr-nitrate solution followed by several mixing, processing and heating steps with YSZ powder as the final product. Losses of Y_2O_3 during these process steps are not reported in any of these publications. Additional requests to manufacturers of such powders (e.g., SulzerMetco) to confirm this did not result in additional information with regard to the proprietary nature of the data. In addition, only some general information could be found. Du and Graedel

(2011a) estimate losses of 10% from fabrication and manufacturing (i.e. including manufacturing of the final product) for REE in general, and in (Du and Graedel 2011c) losses of about 10.4 % are estimated for yttrium on the material level (i.e., not product-specific) for fabrication (of intermediate yttrium products) and 5 % for manufacturing (of final goods). In addition to these losses, Du and Graedel (2011c) report a "phantom flow" of about 6.4 Gg in 2007 (about 57 % referring to the input to manufacturing) which they could not dissolve. With regard to spray powder production, only the losses referring to fabrication are of interest.

Against this background, three scenarios are assessed. In an optimistic scenario losses of 0 % are analyzed –assuming that the lack of data on losses in literature can be interpreted as if no losses occur. In a second scenario, losses of 10 % are assumed based on the Du and Graedel (2011c) data. In addition, losses of 5 % are assumed in a third scenario as an average of the other scenarios. In all three scenarios the losses are assumed to be landfilled. Due to lack of data, these losses are assumed to remain constant until 2030 while the analyzed range of losses can be considered to appropriately cover potential future developments.

Table 63: Yttrium losses in production of spray powder

		2012 pessimistic	2012 modest	2012 optimistic	2030 pessimistic	2030 modest	2030 optimistic
Dissipative losses from spray powder production	$L_{F\&M-I}$	10%	5%	0%	10%	5%	0%
- to landfills	$L_{F\&M-I,lf}$	10%	5%	0%	10%	5%	0%

Coating of aircraft engine parts

Subsequently, the YSZ is used for the coating of the engine parts. The engine parts (blades, vanes and combustor) are commonly coated by air plasma spraying or physical vapor deposition (Krause et al. 2014; Clarke, Oechsner, and Padture 2012; T. Seitz, pers. comm.). Within these processes losses occur in form of overspray. The overspray is collected (as filter cake) together with losses of other materials used for coating of aircraft engines. Of these, many have a significant share of nickel. Up to now, the collected waste material is further processed aiming at a nickel recovery. Other contained materials are so far not recovered (R. Gülzow, pers. comm.).

For the overspray, expert information on the ratio of material input to embodied material has been available. Accordingly, for vanes and blades a factor of 3-5 to account for the ratio of material input to material embedded in the coating needs to be applied. For the combustor this factor is between 1.5 and 2 (P. Döbber, pers. comm.). With consideration of the mass ratio of the different components (blades/vanes to combustor; see below) this means losses of 44.2 % to 81.6 % related to the material

input. Other experts indicated losses of more than 50 % to be an exception in modern coating processes (M. Loges, pers. comm.). Based on this information different scenarios are developed.

In the nickel refinery, the losses can be assumed to end up in the slag (cf. Heegn et al. 2003). These slags might be further processed or directly landfilled (Faulstich et al. 2010). Either way, no recovery of the contained REE will be conducted and the yttrium can be assumed to be used as construction material or to end up on landfills. Based on information from various references (ITAD 2014; Boh and Braga da Silva, Ledomiro 2014; Weitkämper and Wotruba 2014; Wotruba and Weitkämper 2014; Deike, Warnecke, and Vogell 2012; Faulstich et al. 2010) and in accordance with the assumptions regarding slag treatment in the other case studies, a split of dissipative losses to other material flows of 90 %, and 10 % to landfills is assumed.

Based on this, a range of total dissipative losses of 44.2 % to 81.6 % is used in a min, max, and mean scenario for the present situation. Regarding the future development, three different scenarios are assessed. Consultations with experts (manufacturers: LHT, MTU) did reveal a rather low priority of the reduction of overspray due to low economic incentives. Based on this, a modest scenario assuming a 10 % reduction in relation to the mean scenario, an optimistic scenario assuming a 20 % reduction in relation to the min scenario, and a pessimistic scenario assuming constant losses in relation to the 2012 max scenario are assumed. The losses are summarized in Table 64.

Table 64: Losses from coating of aircraft engine parts. Totals may not add up due to rounding differences.

		2012 min	2012 mean	2012 max	2030 min	2030 mean	2030 pessimistic
Dissipative losses from coating	L_{FM-II}	44.2%	62.9%	81.6%	35.4%	56.6%	81.6%
- **to other material flows**	$L_{FM-II,omf}$	39.8%	56.6%	73.4%	31.8%	50.9%	73.4%
- **to landfills**	$L_{FM-II,lf}$	4.4%	6.4%	8.2%	3.5%	5.7%	8.2%

Based on the two considered process steps within fabrication and manufacturing –production of spray powder and coating of aircraft engine parts– the total losses in the F&M stage can be determined by combining the min, mean/modest, and max scenarios from both process stages. The respective scenarios for the total losses are shown in Table 65. Regarding the second step of the F&M stage, i.e., regarding the coating process which corresponds to the manufacturing stage in (Du and Graedel 2011c), the significantly higher losses identified for the coating process need to be mentioned (44.2 % to 81.6 % compared to 5 % referring to manufacturing on material level). At least for the analyzed product, the data from (Du and Graedel 2011c) appears to be improper. In addition, the high losses from the coating process might explain the “phantom flow” from manufacturing identified by Du and Graedel (2011c) to some extent.

Table 65: Total dissipative losses from F&M stage

		2012 min	2012 mean	2012 max	2030 min	2030 modest	2030 max
Dissipative losses from F&M	L_{FM}	44.2%	71.1%	83.4%	39.8%	58.8%	83.4%

Amounts of coating per engine

The average metal concentration (concentration of yttria) in the coating is 8 mol.-% (T. Seitz, pers. comm.; Sulzer Metco 2012b; Sulzer Metco 2012a). Data on the thickness of the coating ranges from 120 (J. Lemke, pers. comm.) to 250 µm (Rolls-Royce 2011). The size of the coated surface and the total amount of required material varies with the engine size. Quite generally, turbines of short, mid, and long distance planes can be distinguished. The coated surface ranges from about 3 m² to 8 m² (Zimmermann and Gößling-Reisemann 2014a).

The amount of YSZ coating is determined based on information from manufacturers (P. Döbber, pers. comm.; T. Seitz, pers. comm.) and given in Table 66. Refining the approach used in (Zimmermann and Gößling-Reisemann 2014a) where only two classes of aircrafts have been distinguished, three different aircraft types (short-, mid, and long-distance) are distinguished in the following. In an engine of a short distance plane, vanes, blades and combustor are coated with YSZ. The following overview shows the amount of material (YSZ) per part as well as the total amount for an engine of a short-distance aircraft (P. Döbber, pers. comm.):

- Vane, stage 1: 10-13 g/unit, 38 units
- Vane, stage 2: 11-14 g/unit, 40 units
- Blades: 2-3g/unit, 64 units
- Combustor: 1.2 – 2 kg

Thus, in total between 2,148 and 3,246 g of YSZ are embodied in an engine of a short distance plane. To obtain the respective amounts of a long distance plane a factor 2 to 2.5 needs to be applied resulting in 4.3 to 8.1 kg per engine while the mid-distance aircraft is located in between the two (P. Döbber, pers. comm.; T. Seitz, pers. comm.). The yttrium amounts are then calculated based on a molar concentration of 8 mol.-%. As shown in Table 66 this ratio is 38.4-44.1 % to 55.9-61.6 %. This ratio has also been used in the calculation of the losses in the coating process (see respective section).

Table 66: Yttrium amounts in aircraft engines [grams of yttrium]

	Vanes		Blades		Combustor		Total	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Short-distance	88.5	113.7	13.8	20.7	129.5	215.8	231.7	350.2
Mid-distance	132.7	199.0	20.7	36.2	194.2	377.6	347.6	612.8
Long-distance	176.9	284.3	27.6	51.8	258.9	539.4	463.4	875.4

One restriction regarding the use of this data has to be mentioned. The data refers to ideal-typical classes of aircrafts that can be differentiated in short-, mid-, and long-distance planes. In reality, such a differentiation is not always strictly possible (see also section 5.4.3 Use Phase / Determining material flows into use phase). Airplanes within these classes differ in terms of their engine design and some airplane types operate on different distances. Data for each aircraft type was, however, not available, and the differentiation based on the described classes is considered an adequate approach given the limitations of the data.

5.4.3 USE PHASE

The use phase of TBC, i.e., the use phase of aircraft engines and aircraft, respectively, consists of the actual air traffic and regular maintenance.

Air traffic

Dissipation of the thermal barrier coating and the embodied yttrium during aircraft operations is principally possible. Nevertheless, fissures within the coating and deformations of the coating, and not abrasion, appear to be the main limiting factors regarding the coating's maximum lifespan and the main reason for its replacement in regular service intervals (Trunova et al. 2008; J. Lemke, pers. comm.; T. Seitz, and H. Kassner, pers. comm.). Especially for aircrafts that operate within or to and from Germany, abrasion or dissipation of ceramic coating is negligible according to expert information (T. Seitz, and H. Kassner, pers. comm.; cf. Zimmermann and Gößling-Reisemann 2014b). In contrast to this, in aircrafts operating mainly in desert-like or sandy environments, a rather significant share of the coating can be lost between maintenance intervals (T. Seitz, and H. Kassner, pers. comm.; cf. Zimmermann and Gößling-Reisemann 2014b). Analyses based on aircrafts mainly operating in the middle-east showed losses of more than 50 % of the coating after 60 cycles (starts and landings) (Naraparaju et al. 2014). An older study describes TBC losses of up to 3 % after 10,000 flight hours without providing details on the geographic scope (Toriz, Thakker, and Gupta 1989). Here, a significant increase in the rate of abrasion after 10,000 h has been observed, resulting in 10% losses after 16,000 flight hours (Toriz, Thakker, and Gupta 1989). This indicates that dissipation of coating within aircraft operations is possible and might occur, although it is not considered to occur in a relevant scale by the consulted experts. Based on this, two scenarios with dissipative losses of 3 % and 10 % of the coating are assessed.

Table 67: Dissipative losses of TBC within aircraft operations

		2012 / 2030 low	2012 / 2030 high
Dissipative losses	L_{Use-I}	3%	10%
- **to the environment**	$L_{Use-I,env}$	3%	10%

Maintenance

In regular maintenance intervals the components are checked and when considered fit are recoated. The coated components of aircraft engines are usually used for 1 to 4 maintenance use-cycles; 2 use-

cycles can be assumed as an average (R. Burmeister, and P. Döbber, pers. comm.), i.e., on average the engine parts are recoated once. Before the recoating, the old coating is commonly removed using processes such as high pressure water blasting (for the combustor), aluminum oxide blasting (for blades and vanes), and seldom by chemical treatment (R. Burmeister, and P. Döbber, pers. comm.). The waste from water blasting and chemical treatment is usually collected and incinerated, waste from aluminum oxide blasting is landfilled according to expert information (R. Gülzow, pers. comm.). Assuming a weight-ratio of the coating of vanes/blades to combustor of 38.4 %-44.2 % to 55.9 %-61.6 % gives the shares of material treated by direct landfilling and incineration, respectively. In the case of incineration, however, the residues (slags and ashes) partly go directly to landfills (about 10 %). 41 % are used in the construction of landfills, and 31 % are used in road constructions, i.e., can be considered to enter another material flow. The balance is used for other construction purposes (Faulstich et al. 2010; Huang, Bird, and Heidrich 2007; Motz and Geiseler 2001). Based on the shares given by Faulstich et al. (2010) (10 % of incineration residues are landfilled, 90 % are used for construction purposes, i.e., enter other material flows), and in accordance with the assumptions regarding slag treatment in the other case studies, the dissipation rates can be calculated as shown in Table 68. Future changes of the treatment of slags are possible and are frequently discussed, however, mainly regarding metallurgical slags (cf. section 5.4.4). Nevertheless, it seems likely that until 2030 there will be a REE recovery on a significant scale. Thus, shifts between the receiving media (landfills and other material flows) are possible, but no reduction of the total dissipative losses is to be assumed. Against this background, the allocation to landfills and other material flows is considered to remain constant. The removal of the coating is then followed by a re-coating according to the description given in section 5.4.2.

It has to be noted, that in maintenance (removal of the coating) the total material losses amount to 100 % of the input flows and on average parts are only re-coated once. I.e., within maintenance 50 % of the components are not re-coated but discarded as described in section 5.4.4.

Table 68: Dissipative losses in maintenance of coated engine parts. Loss rates refer to coating removal processes, loss rates in parentheses refer to input to maintenance. Totals may not add up due to rounding differences.

		2012-2030 A	2012-2030 B
Dissipative losses in maintenance	L_{Use-II}	100% (50%)	100% (50%)
- **to landfills**	$L_{Use-II,lf}$	44.56% (22.28%)	49.69% (24.85%)
- **to other material flows**	$L_{Use-II,omf}$	55.44% (27.72%)	50.31% (25.16%)

Based on the scenario regarding the losses in aircraft operation and maintenance the total dissipative losses in the use phase are determined as shown in Table 69 based on an average of two cycles per coated part. The numbers refer to the material input into use phase, i.e., it is assumed that the coated turbine parts are discarded after an average of two use cycles.

Table 69: Dissipative losses in use phase of TBC

	Parameter	Scenario & Year			
		2012/2030 A	**2012/2030 B**	**2012/2030 C**	**2012/2030 D**
Total dissipative losses in use phase	L_{Use}	51.5%	51.5%	55%	55%
- **to the environment**	$L_{Use,env}$	3%	3%	10%	10%
- **to landfills**	$L_{Use,lf}$	21.61%	24.10%	20.05%	22.36%
- **to other material flows**	$L_{Use,omf}$	26.89%	24.40%	24.95%	22.64%

Length of maintenance intervals and total lifespan

The average time between maintenance intervals ranges from about 8,000 to 10,000 flight hours for short-distance aircrafts, to 20,000 to 23,000 for long-distance aircrafts; mid-distance aircrafts are located between the two (J. Lemke, pers. comm.; T. Seitz, pers. comm.; U. Schulz, pers. comm.). The higher frequency of maintenance of short and mid-distance planes is due to the increased number of starts and landings compared to long-distance planes which means a higher stress for TBC as well as other aircraft components. Nevertheless, all considered types of aircrafts have an equal number of flight hours per year of about 4,000 hours (Zimmermann and Gößling-Reisemann 2014a). Based on both numbers, time between maintenance intervals and flight hours per year, the lifespan of the coatings can be determined (see Table 70).

Table 70: Lifespan of TBC in aircraft engines

	Time between maintenance intervals [hours]		Flight hours per year	Lifespan of TBC [years]	
	Min	**Max**		**Min**	**Max**
Short-distance	8,000	10,000	4,000	2	2.5
Mid-distance	14,000	16,500	4,000	3.5	4.125
Long-distance	20,000	23,000	4,000	5	5.75

Determining material flows into use phase

The material flows into use are determined based on the number of engines in use which results from the number of aircrafts in use. The geographic focus on Germany is not strictly applicable here, and the number of aircrafts used by the five leading airlines has been used as a basis for the calculations. These five airlines, Lufthansa German Airlines, Air Berlin, Germanwings, TUIfly, and Condor Aviation Services cover 98 % of all flights operated by German airlines (DLR 2011). The data basis for the calculation includes the present stock of airplanes of these airlines as well as reported orders for future deliveries of aircrafts and forecasts regarding the future development.

Regarding the stock of airplanes in 2012/2013, data available from the airlines' websites have been used. The composition of the stock of aircrafts is given in Appendix C) in Table A 66 comprising 654

airplanes with a total of 1,500 engines. The table also includes information on the distances on which the aircrafts are used; a strict differentiation between short-, mid-, and long-distance is not always possible, though. In the cases where airplanes are indicated to be used on short- and mid-distance or mid- and long-distances, a 50-50 split has been assumed, and the planes have been assigned to the different classes accordingly.

Regarding the future development a steady growth is expected. For the years 2010-2029 Clearwater (2011) reports 6,825 orders in the backlogs of airbus and Boeing, of which 1,396 (about 20 %) come from European countries. For Germany, data on orders up to year 2025 are available (cf. Zimmermann and Gößling-Reisemann 2014a; Zimmermann and Gößling-Reisemann 2014b). However, these data are fragmentary and subject to future changes regarding potential additional orders as well as withdrawals. Hence, general forecasts on the future development of air traffic etc. are preferred over data on reported orders. Clarke, Oechsner, and Padture (2012) assume a doubling of aircraft stock in the next twenty years. Airbus (2013) assumes air traffic and fleets to double within the next 15 years. Although this forecast includes a significant growth in the Asia-Pacific region, a relevant share (about 20 %) of new additions to aircraft fleets is assumed to be situated in Europe with an annual growth of 3.3 % (Airbus 2013). Boeing (2014), as well, assumes global aircraft fleets to double within the next 20 years, although a slightly more moderate growth is expected for Europe. Here, aircraft fleets are assumed to grow annually by about 2.9 % resulting in a growth of about 77 % until 2033 (Boeing 2014).

Based on the projections by airbus and Boeing, an annual growth of 2.5 % to 3.5 % until 2030 is assumed for the German market. The same growth is assumed for short-, mid-, and long-distance planes. The development for both scenarios is given in Appendix C) in Table A 66.

The stock and flows of yttrium are determined as a function of the engine stock. As described above, the coated engine parts are re-coated or replaced in regular maintenance intervals. The average lengths of these service intervals have been given in Table 70. As described and indicated by the consulted experts, the actual time between these service intervals (i.e. the lifespan of the TBC) varies around the given average time spans. Therefore, assuming a distribution such as the Weibull distribution might be more appropriate than modelling the TBC's discard patterns using a simultaneous exit function. However, no data supporting the choice of a particular function has been available. To deal with this, the Weibull distribution has been selected and the shape parameter k has been varied. Values for *k* of 1.5, 2 (cf. Zimmermann and Gößling-Reisemann 2014a; NIES 2010), 3.602 (approximating a normal distribution, cf. section 4.4.4) and 100 (approximating a simultaneous exit function) are analyzed. A variation of these values showed the highest values regarding the input flows (mean of annual input flows) for k=1.5 and the lowest values for k=100, which are therefore selected as settings for max and min scenario, respectively. However, the variation of the shape parameter appeared to have only a marginal influence on the absolute material flows with variations of <1 % in the min scenario and <2.7 % in the max scenario.

Theoretically, to accurately model the flows out of use and the corresponding replacement of in-use stock which results in new flows into use, knowledge about historic input flows is required reaching back to the year of the first introduction to the market, as described in section 4.4.5. As data availability does not permit including these flows, a simplified approach is taken, assuming a homogenous age distribution within the 2012 stock.

The parameter settings for min and max scenario are summarized in Table 71. Based on these parameter settings, the flows into use are calculated. In the min scenario the flows into use increase from 140.5 kg in 2012 to 177.3 kg in 2030. In the max scenario the input flows increase from 239.5 kg in 2012 to 346.3 kg in 2030. The development of input flows from 2012-2030 for both scenarios is shown in Figure 34.

Table 71: Assumptions for Min and Max Scenario of yttrium flows into use

	Min scenario	Max scenario
Coating: Grams of yttrium per aircraft engine short-/ mid-/ long-distance	231.7 / 347.6/ 463.4	350.2 / 612.8 / 875.4
Lifespan short-/ mid-/ long-distance	2.5 / 4.125 / 5.75	2 / 3.5 / 5
Shape parameter k	100	1.5
Growth rate of stock	2.5%	3.5%

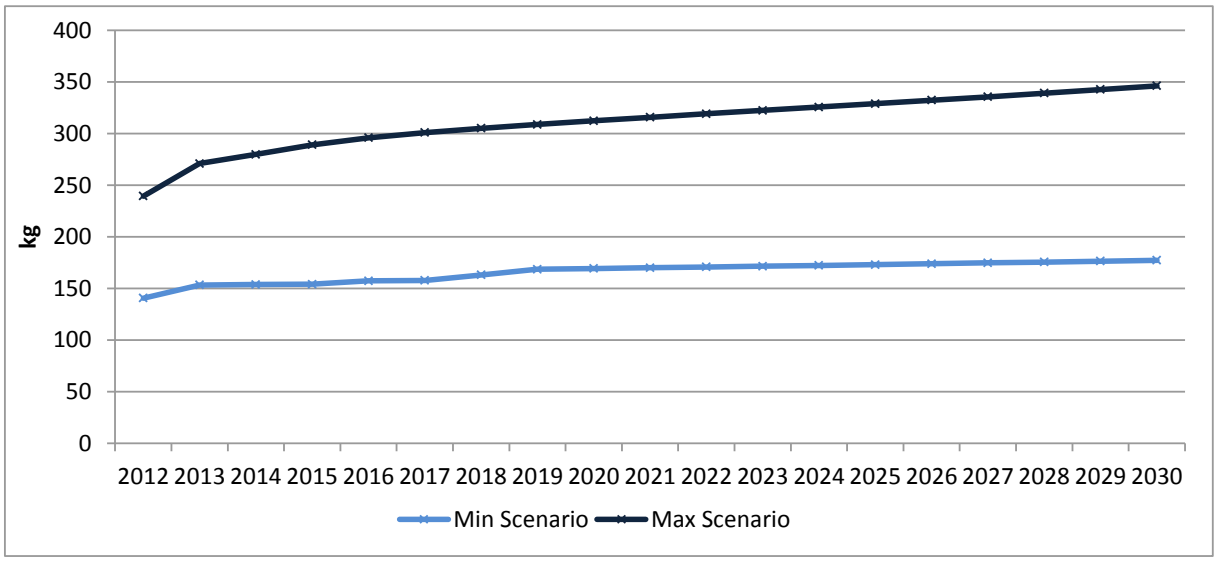


Figure 34: Yttrium flows into use

5.4.4 End-of-Life

The coated engine parts enter the EOL stage when they are found unsuitable for re-coating which is the case after an average of 2 cycles (as described in section 5.4.3 Use Phase \ Maintenance). When the coated components are discarded, they usually go to metal recovery (usually nickel recovery as turbine components mainly consist of nickel based super alloys) (T. Seitz, and H. Kassner, pers. comm.) and no yttrium recovery is practiced. The yttrium than ends up in the slag (based on Heegn et al. 2003). Further processing of metallurgical slags is frequently discussed (e.g., Nadirov et al. 2013; Binnemans et al. 2013b; Jones et al. 2013) and practiced in some cases. The recovery of REE in

particular is discussed by Binnemans et al. (2013b) but so far not practiced on a relevant scale. Also, even when assuming a future increased REE recovery from metallurgical slags, it does not seem likely that the focus will be on low concentrated yttrium. In accordance with the assumptions regarding slag treatment in the other TBC life cycle stages, the other case studies, and literature (ITAD 2014; Boh and Braga da Silva, Ledomiro 2014; Deike, Warnecke, and Vogell 2012; Faulstich et al. 2010), 90 % dissipative losses to other material flows (use of slags as construction material) and 10 % to landfills are assumed.

Table 72: Dissipative losses at EOL of TBC

	Parameter	2012 /2030
Dissipative losses from EOL	L_{EOL}	100%
- **to other material flows**	$L_{EOL,omf}$	90%
- **to landfills**	$L_{EOL,lf}$	10%

5.4.5 Results: Material Flows along the Life Cycle

Based on the different parameter settings described regarding the different life cycle stages, various scenarios have been analyzed. A summary of the parameter settings of the analyzed scenarios is given in Table 73, for each scenario the min and max flows have been analyzed as summarized in Table 71. The baseline setting of the parameters which defines the min and max baseline scenario is indicated in the table by shading of the respective cells. Besides the baseline scenarios, major characteristics of the alternative scenarios are highlighted in the following, while the complete results for each scenario (min and max results) are given in Appendix C) in Table A 68 to Table A 85.

Table 73: Summary of analyzed scenarios along the life cycle of thermal barrier coatings in aircraft engines. Shading indicates the parameter setting of the baseline scenario.

Life cycle stages/ scenarios	Parameter	Scenario & Year					
Material production scenario		**2012 C**	**2012 A**	**2012 B**	**2030 C**	**2030 A**	**2030 B**
Dissipative losses	L_{MP}	50%	28%	28%	50%	21%	13.84%
- **to the environment**	$L_{MP,env}$	0.5%	0.3%	0.3%	0.5%	0.2%	0.1%
- **to other material flows**	$L_{MP,omf}$	0.5%	0.3%	0.3%	0.5%	0.2%	0.1%
- **to landfills**	$L_{MP,lf}$	49%	27.4%	27.4%	49%	20.6%	13.64%
Fabrication & manufacturing: spray powder production scenarios		**2012 pessimistic**	**2012 modest**	**2012 optimistic**	**2030 pessimistic**	**2030 modest**	**2030 optimistic**
Dissipative losses	$L_{F\&M-I}$	10%	5%	0%	10%	5%	0%
- **to landfills**	$L_{F\&M-I,lf}$	10%	5%	0%	10%	5%	0%
Fabrication & manufacturing: coating		**2012 max**	**2012 mean**	**2012 min**	**2030 pessimistic/ max**	**2030 modest/ min**	**2030 optimistic/ min**
Dissipative losses	$L_{F\&M-II}$	81.6%	62.9%	44.2%	81.6%	56.6%	34.4%
- **to other material flows**	$L_{F\&M-II,omf}$	39.8%	56.6%	73.4%	31.8%	50.9%	73.4%
- **to landfills**	$L_{F\&M-II,lf}$	4.4%	6.4%	8.2%	3.5%	5.7%	8.2%
Use phase: Aircraft operation scenarios		**Low in-use dissipation**			**High in-use dissipation**		
Dissipative losses	L_{Use-I}	3%			10%		
- **aircraft operations to the environment**	$L_{Use-I,env}$	3%			10%		
Use phase: Maintenance Scenario		**2012/2030 A**			**2012/2030 B**		
Dissipative losses	L_{Use-II}	50%			50%		
- **to landfills**	$L_{Use-II,lf}$	22.28%			24.85%		
- **to other material flows**	$L_{Use-II,omf}$	27.72%			25.16%		
End-of-life		**2012 / 2030**					
Dissipative losses	L_{EOL}	100%					
- **to other material flows**	$L_{EOL,omf}$	90%					
- **to landfills**	$L_{EOL,lf}$	10%					

Baseline scenario

The results of the baseline scenario show a complete dissipation of yttrium along the TBC life cycle. Figure 35 visualizes the material flows for selected years (2012, 2021, and 2030). The most relevant processes in terms of dissipative losses are the coating process and the material production stage. Dissipative losses from material production mainly go to landfills; dissipative losses from coating mainly go to other material flows, and a smaller share goes to landfills. The dissipative losses from coating account for 43 % of the total dissipation in 2012 and slightly increase to 44 % until 2030. Dissipation from material production accounts for 28 % of the total dissipative losses in 2012 which decreases to 21 % in 2030. The EOL stage and the maintenance stage account for about 12 % of the total dissipative losses in 2012 with a slight increase to about 15 % in 2030. Dissipation from EOL and maintenance goes to both, landfills and other material flows. The use phase shows relatively small dissipative losses compared to the other life cycle stages of about 1 % of the total dissipation while it is still the major source for dissipation to the environment. In total, however, dissipative losses to the environment and other material flows have only a rather minor relevance compared to dissipation to landfills which are the receiving medium for 93-99 % of the total yearly dissipation.

In the min scenario the absolute total annual dissipation in 2012 is 554 kg, peaks at 586 kg in 2019 and decreases to 526 kg in 2030. In the max scenario it amounts to 944 kg in 2012, peaks at 1,068 kg in 2021, and decreases to 1,008 kg in 2030. In the considered timeframe from 2012 to 2030 in total about 11,234 kg and 19,688 kg of yttrium, respectively, dissipate. In the min scenario, the annual material demand (required input of elementary yttrium to fabrication and manufacturing stage) amounts to 399 kg in 2012, peaks at 449 kg in 2019 and decreases to 430 kg in 2030. In the max scenario the material demand in 2012 is 679 kg and increases to 840 kg in 2030. The CDL amounts to 11,234 kg in the min scenario, and 19,688 kg in the max scenario.

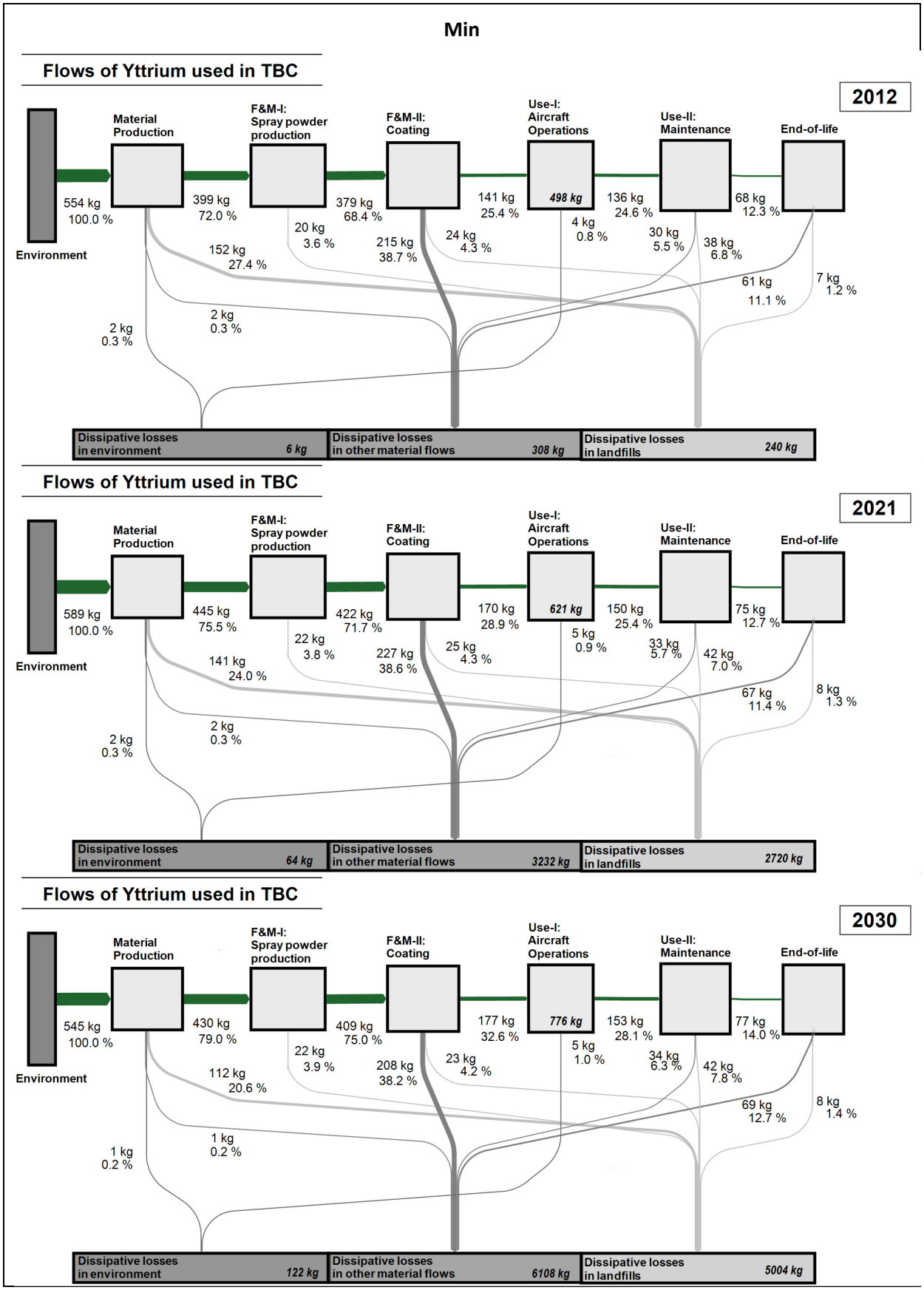


Figure 35: Material stocks and flows in selected years in TBC baseline scenario; relative material flows refer to input flow from environment (=100%), relative in-use stocks refer to 2012 in-use stock (=100%); percentages may not add up to 100% due to rounding differences.

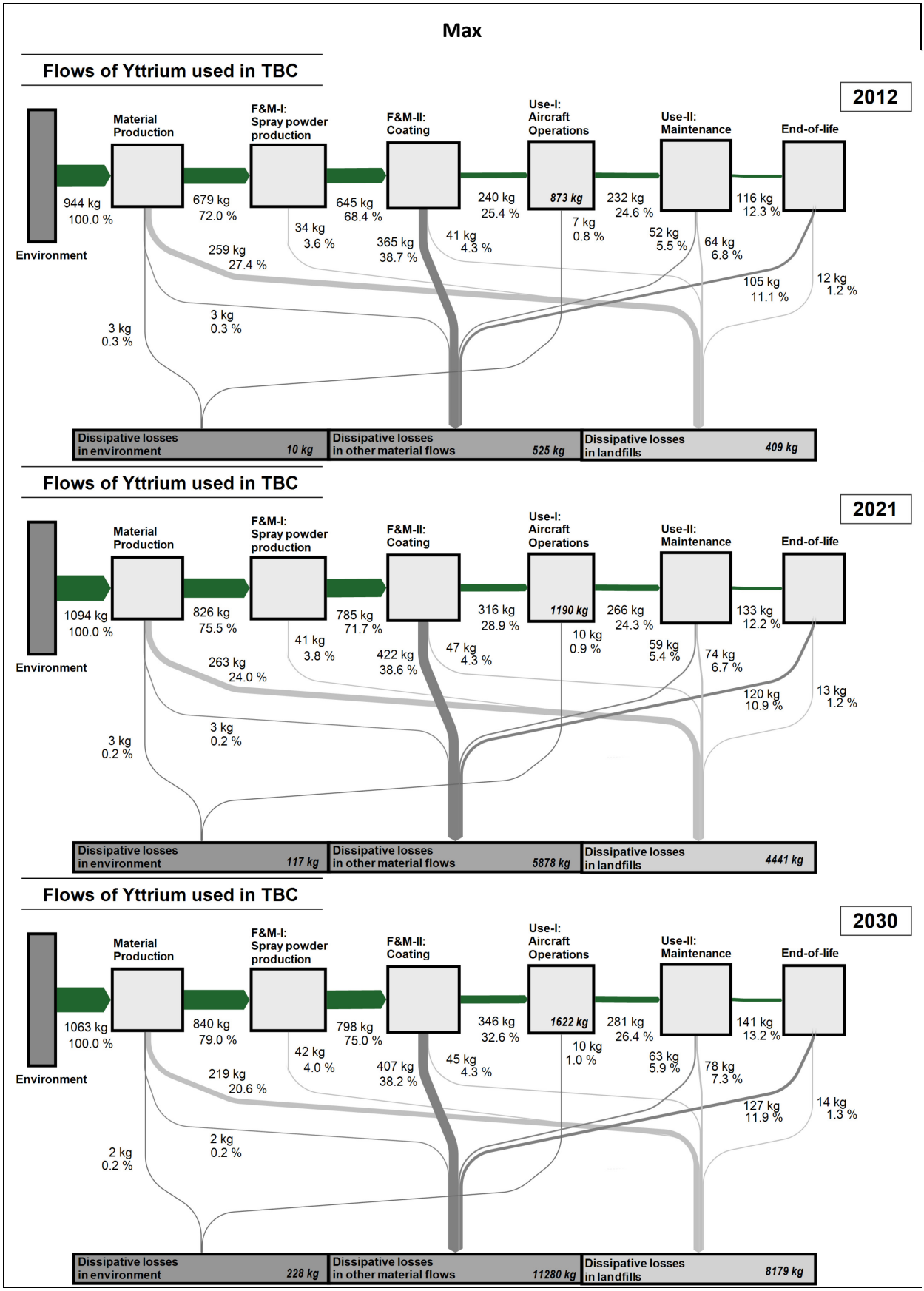


Figure 35 continued.

Variation of material production stage

The alternative scenarios (scenario B and scenario C) concerning the material production stage result in increased or decreased dissipative losses from the material production stage and, accordingly, an increased or decreased material input from the environment. While in the scenario B a more optimistic development of recovery efficiencies is assumed, in scenario C higher losses which include process routes not aiming at yttrium recovery are assumed. Thus, the scenario C means an expansion of the system boundaries analogous to the analysis of the material production stage in the other case studies. The lack of reliable data regarding the material production stage has to be considered, though, when interpreting the results.

The analyzed variations of the material production stage show a significant impact on the overall results. As summarized in Table 74, material flows from the environment to the material production stage show a significant reduction in scenario B, while they increase significantly in the scenario C. Correspondingly, dissipative losses –particularly to landfills– increase and decrease, respectively. In terms of total yearly dissipation, scenario B shows a maximum of 580 kg in the min and 1,043 kg in the max scenario, while scenario C shows a maximum of 883 kg and 1,625 kg, respectively. The CDL is increased by 50 % in scenario C. In scenario B it is reduced by 4-5 %. The material flows of scenario C are visualized in Figure 36.

Table 74: Comparison of selected material flows - Baseline scenario and MP variations

Material flow	Scenario	2012	2021	2030
Input from environment	Baseline min/max	554/944 kg	589/1,094 kg	545/1,063 kg
	MP pessimistic min/max	798/1,359 kg	889/1,652 kg	860/1,680 kg
	MP optimistic min/max	554/944 kg	562/1,044 kg	499/975 kg
Dissipation to landfills	Baseline min/max	240/409 kg	238/438 kg	207/398 kg
	MP pessimistic min/max	479/816 kg	532/985 kg	516/1,002 kg
	MP optimistic min/max	240/409 kg	212/390 kg	163/312 kg
Total yearly dissipation	Baseline scenario	554/944 kg	574/1,054 kg	526/1,008 kg
	MP pessimistic min/max	798/1,359 kg	874/1,612 kg	841/1,625 kg
	MP optimistic min/max	554/944 kg	547/1,004 kg	480/920 kg

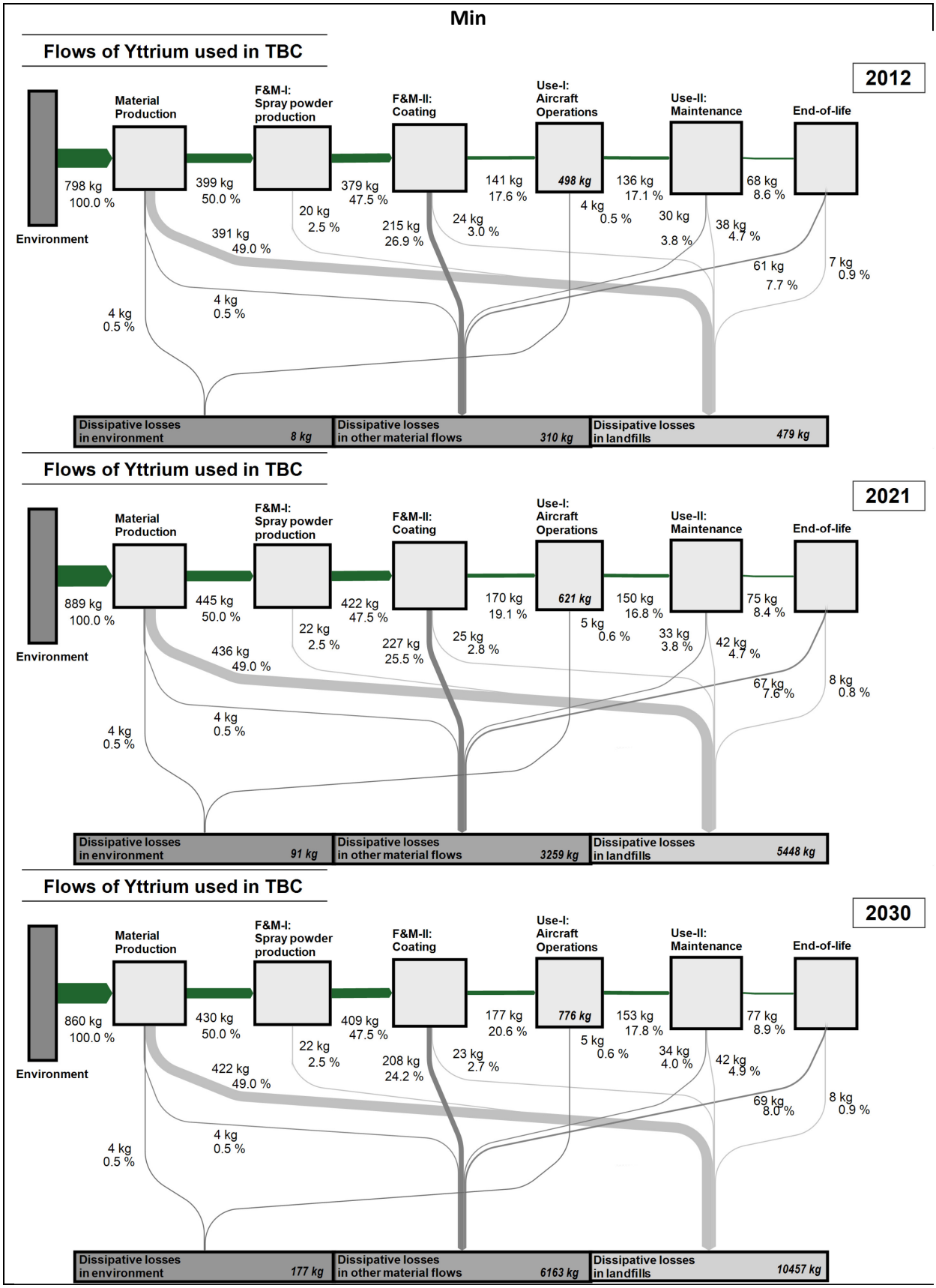


Figure 36: Material stocks and flows in selected years in yttrium MP scenario C; relative material flows refer to input flow from environment (=100%), relative in-use stocks refer to 2012 in-use stock (=100%); percentages may not add up to 100% due to rounding differences.

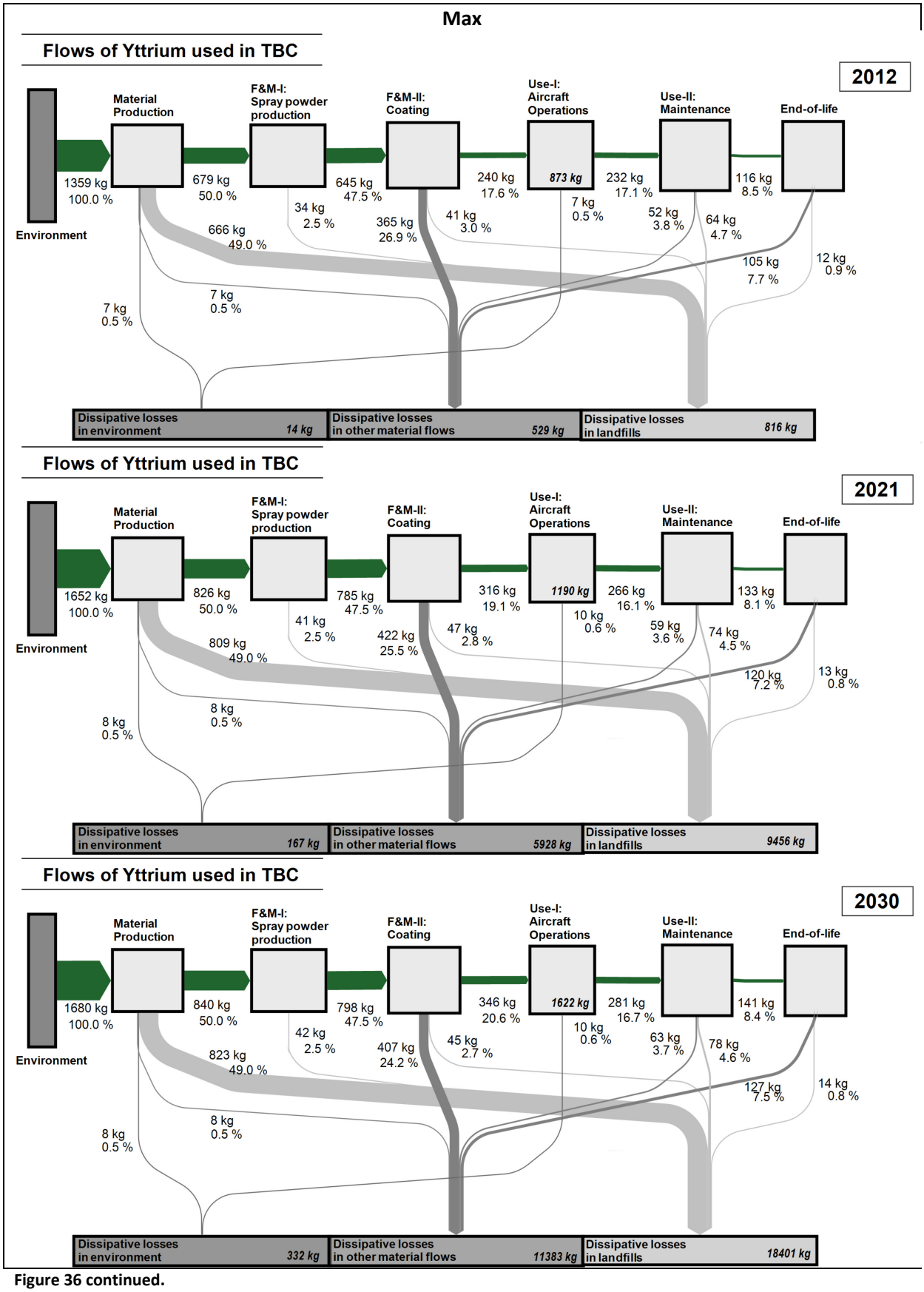


Figure 36 continued.

Variation in fabrication and manufacturing

In the fabrication and manufacturing stage, changes to the spray powder production process as well as the coating process have been analyzed. The analyzed changes to the spray powder production process did not result in significant changes to the material flows in the min scenario; in the max scenario changes of input flows and dissipative losses of about 10 % can be observed.

Major changes of material flows resulted from variations in the coating process. The assumptions of the pessimistic scenario lead to a threefold increase of dissipative losses and material demand. In the optimistic scenario on the other side dissipation and material demand were reduced by a factor of about 2. The material flows for 2012, 2021, and 2030 for both scenarios are visualized in Figure 37 and Figure 38, which clearly show the resulting changes.

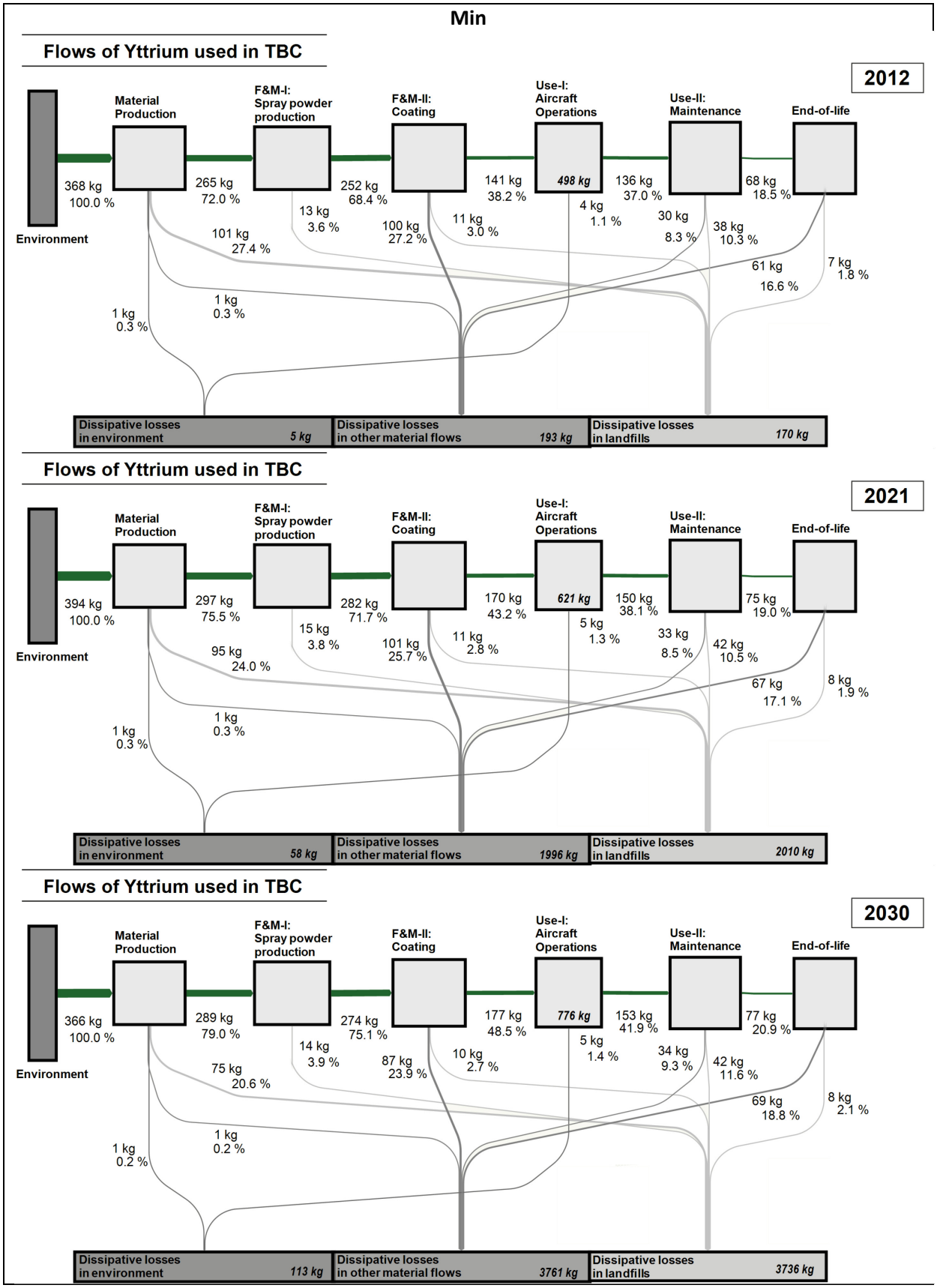


Figure 37: Material stocks and flows in selected years in alternative TBC F&M coating scenario (optimistic); relative material flows refer to input flow from environment (=100%), relative in-use stocks refer to 2012 in-use stock (=100%); percentages may not add up to 100% due to rounding differences.

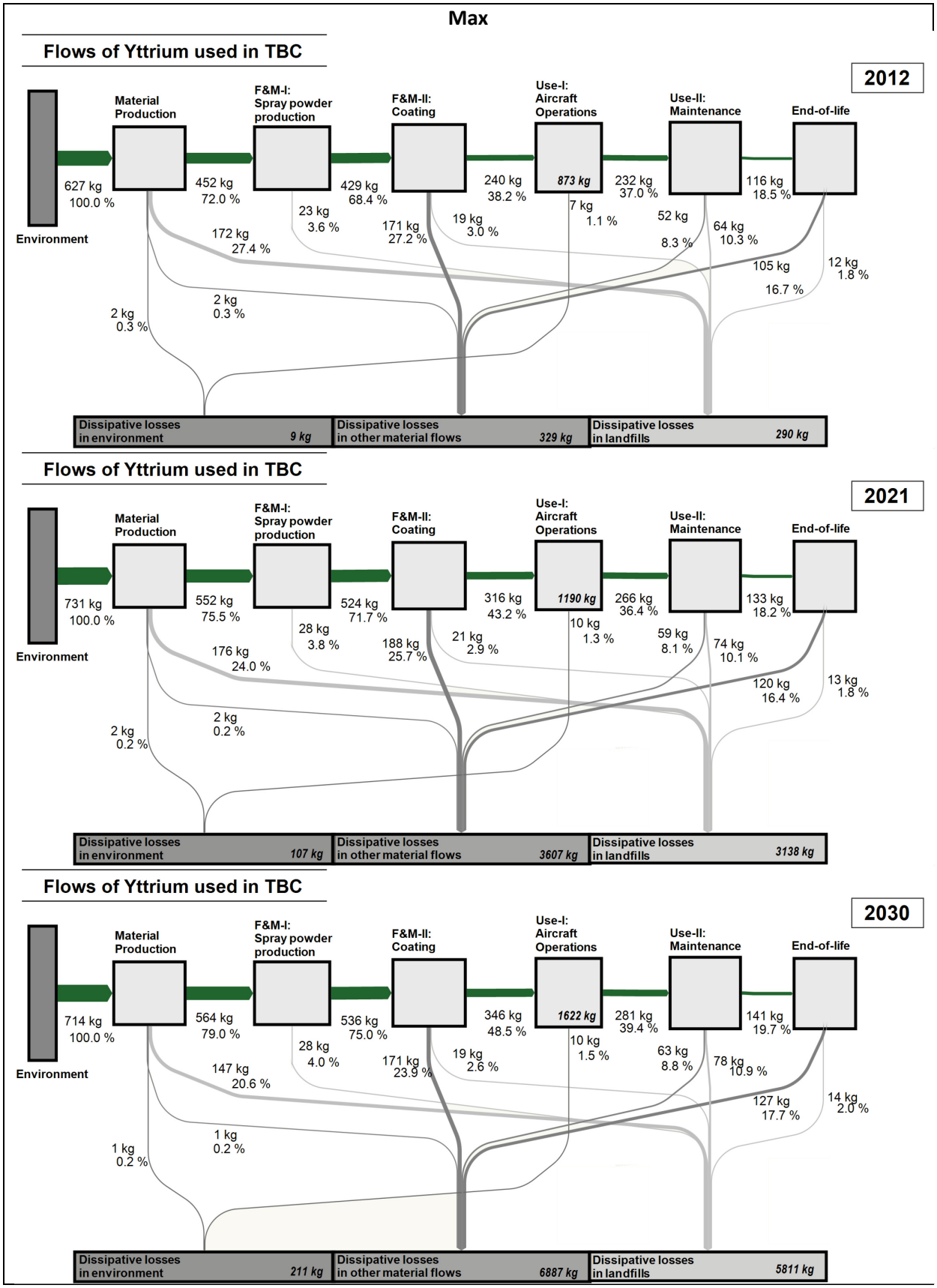


Figure 37 continued.

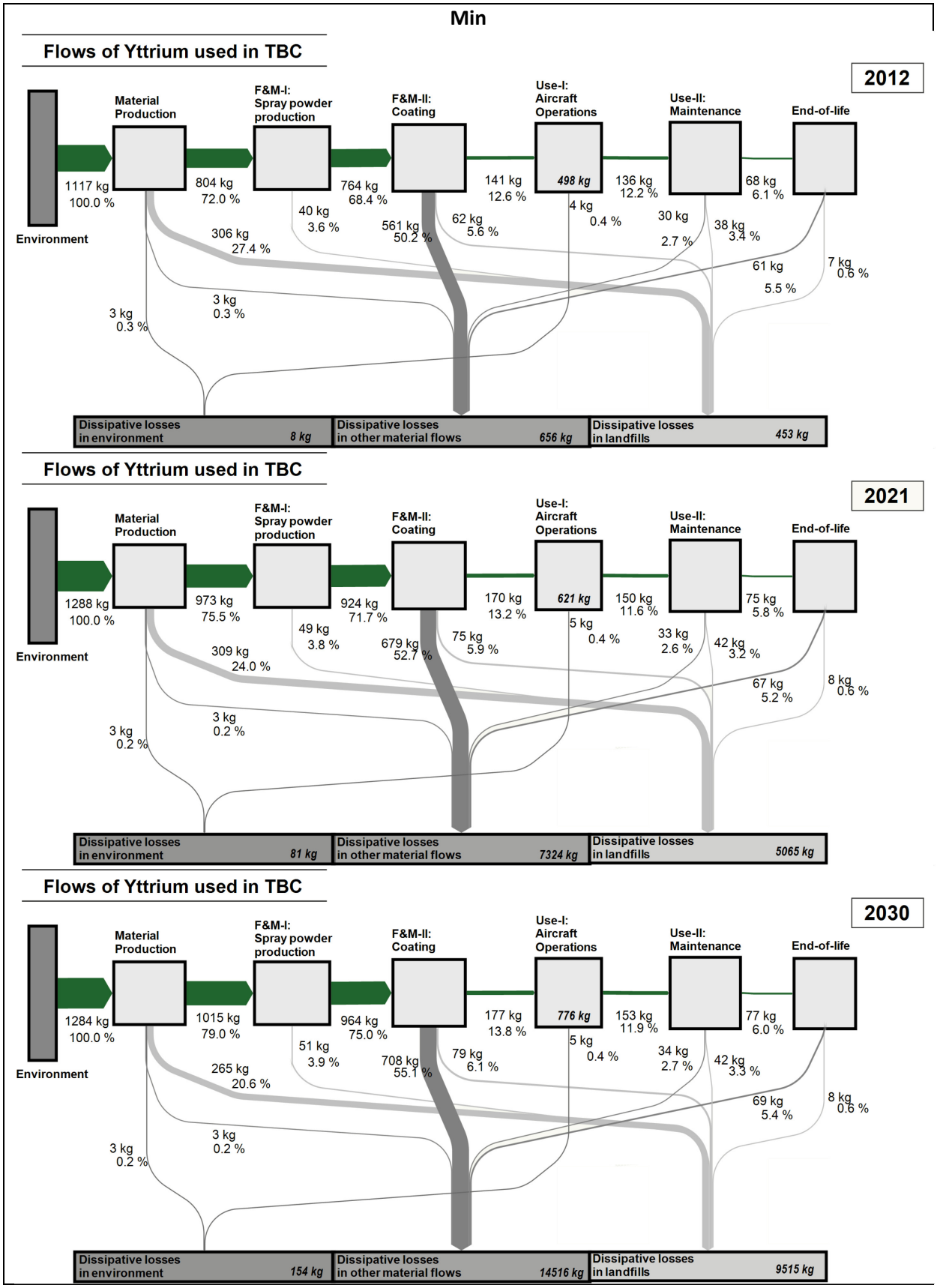


Figure 38: Material stocks and flows in selected years in alternative TBC F&M coating scenario (pessimistic); relative material flows refer to input flow from environment (=100%), relative in-use stocks refer to 2012 in-use stock (=100%); percentages may not add up to 100% due to rounding differences.

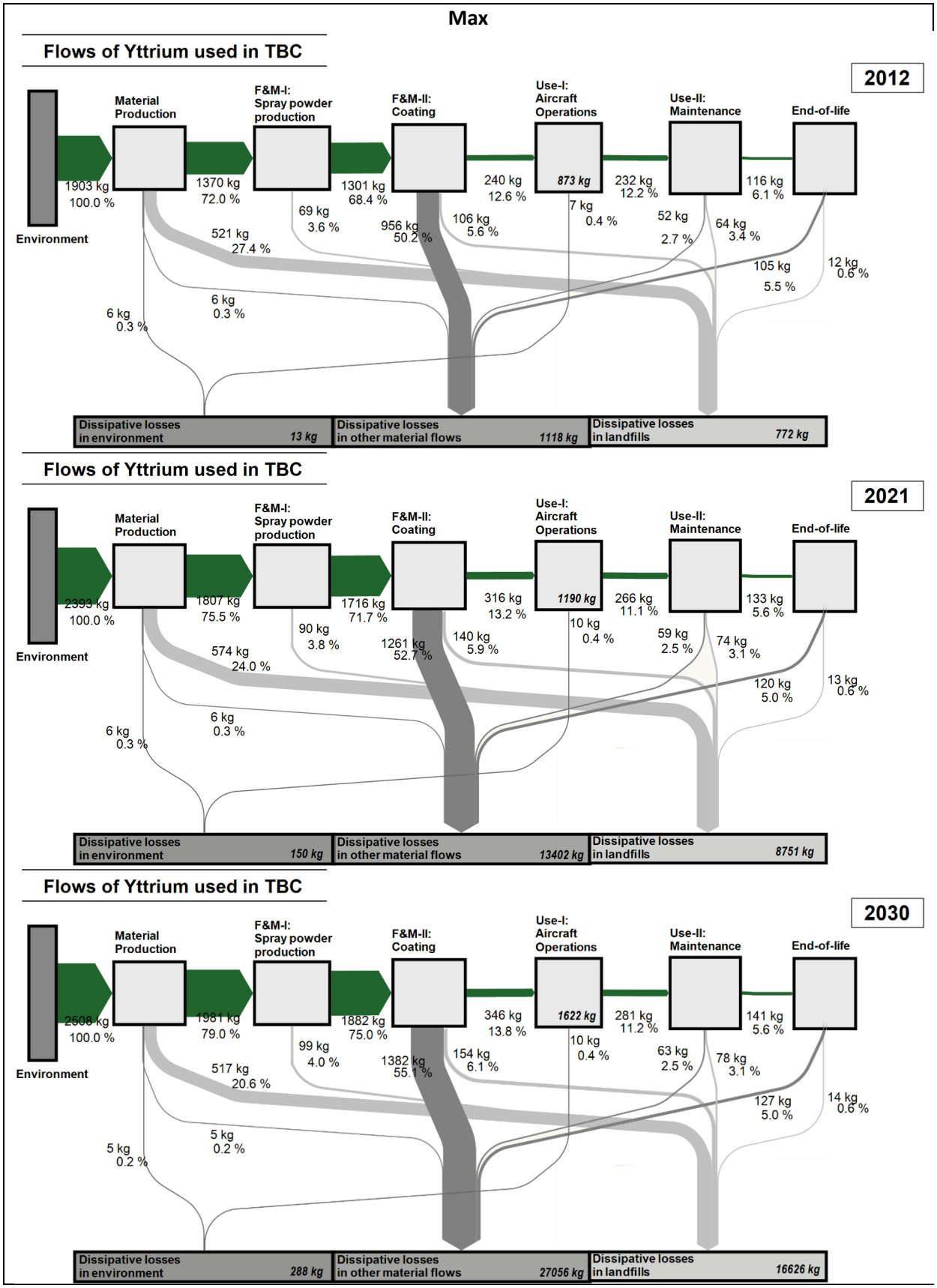


Figure 38 continued.

Variations in use phase

In the use phase, parameters concerning in-use dissipation as well as waste treatment in maintenance have been varied. Changes regarding the maintenance stage did not result in significant changes to the material flows.

The variation of the in-use dissipation did not result in major changes to the overall results, either. However, the variation of the in-use dissipation increased the total annual dissipation to the environment by almost a factor of three: In the min scenario, the cumulative dissipation to the environment increases to 343 kg in 2030 compared to 122 kg in the baseline scenario. In the max scenarios dissipation to the environment amounts to 642 kg in 2030 compared to 228 kg in the baseline scenario.

Summary

The cumulative dissipative losses from 2012 to 2030 are summarized in Table 75 for the analyzed scenarios. The highest reductions are shown in the optimistic F&M II (coating process) scenario, while the corresponding pessimistic scenario shows the highest increase of dissipative losses. A rather high increase of dissipative losses can also be observed for the pessimistic MP scenario in which the defined system boundaries have been expanded. All other scenarios show a maximum variation of CDL of ±6 % compared to the baseline scenarios.

Table 75: Summary of cumulative dissipative losses in different TBC scenarios

		Cumulative dissipative losses [kg]		Change from baseline scenario	
		Min	**Max**	**Min**	**Max**
Baseline scenario		11,234	19,688	-	-
Material production	**Pessimistic**	16,796	30,116	+50%	+53%
	Optimistic	10,759	18,786	-4%	-5%
F&M I	**Pessimistic**	11,841	20,823	+5%	+6%
	Optimistic	10,688	18,666	-5%	-5%
F&M II	**Pessimistic/ Max**	24,184	43,970	+115%	+123%
	Optimistic/ Min	7,610	12,909	-32%	-34%
In-use I	**High**	11,211	19,742	0%	0%
In-Use II (Maintenance)	**Scenario B**	11,310	19,688	+1%	0%

5.4.6 Conclusions & Discussion

There is a complete dissipation of yttrium along the life cycle of thermal barrier coatings. The coating process appears to be the major “hot spot” in the TBC life cycle followed by the material production stage. Regarding the coating process, the analysis showed that the wide application of more efficient technologies –that are already available and partly in operation– as well as further future improvements could reduce dissipation significantly, roughly by about 34 % (referring to CDL) in the analyzed scenario. Still, even then losses of about 40 % of the input material would occur in the coating pro-

cess. A recovery of yttrium from the respective waste streams appears to be unfeasible and unlikely within the considered timeframe.

Material production as the second most relevant “hot spot” in the TBC life cycle shows dissipative losses that are slightly smaller than the losses from the coating stage. Still, the weak data availability regarding the material production stage needs to be highlighted. Future price increases for rare earth metals might provide the necessary incentives for further increases of process efficiencies in the future. Compared to the production of the other considered metals –indium, gallium, and germanium– and the resulting methodological challenges, the situation is somewhat different regarding yttrium. Yttrium is not produced as a by-product from a bulk-metal like aluminum or zinc but is a co-product in the production of various rare earth elements. This means, in yttrium production there is not a carrier metal that might not be processed regarding a recovery of by-products as it is the case for germanium or gallium. Still, some uncertainties –as described in section 5.4.1– exist but can be assumed to be well covered by the different assessed scenarios.

Regarding the spray powder production only little data has been available. Still, the available data indicated only minor losses. Regarding the use phase, it can be concluded that in-use dissipation does not occur in a relevant scale in any of the analyzed scenarios. It is, however, the main source for dissipation to the environment. Also, data quality regarding in-use dissipation could be further improved. In the maintenance stage, the analysis showed a complete dissipation of the removed material. Future changes are unlikely due to a lack of economic incentives (R. Winter, pers. comm.). Still, based on information from the consulted experts, principally good prerequisites for recycling are given as the removed coating could easily be collected separately. In reality, however, it is collected together with various other wastes reducing the feasibility of recycling considerably. There are some uncertainties regarding the future treatment of the removed coating, but they only result in minor changes regarding the receiving media. At end-of-life, yttrium is not recovered and future changes are unlikely. Of course, a removal of the coating as conducted in maintenance is theoretically possible, but would result in additional costs. As there are no incentives for recycling yttrium from maintenance waste, future recycling from EOL wastes is even more unlikely.

The rather high losses to landfills (5,000 to 8,180 kg in the baseline scenario) and other material flows (6,108 to 11,280 kg in the baseline scenario; almost exclusively use of slags for construction purposes) indicate an increasing potential for urban and landfill mining. In case of increasing metal prices and feasible processes, infrastructure and landfills might develop into relevant yttrium sources.

Some general uncertainties result from the classification of aircrafts into three classes –short-, mid-, and long-distance. This classification might not always be completely appropriate as described in section 5.4.2. Potential deviations will, however, mainly influence absolute material flows and only a minor influence on relative dissipation. Furthermore, the absolute input flows into use “leap” in the first years of the considered period. These leaps result from the modelling approach and the assump-

tions regarding the age structure of the stock in 2012. In 2012 a homogenous age distribution within the stock has been assumed. In every year after 2012 a fixed share of this homogenous stock is replaced. The replacement of the annual additions to the stock, however, starts only with some delay as it is determined by the average lifespans of short-, mid-, and long-distance aircraft and the Weibull parameters. In the first years of the considered timeframe this leads to the observed leaps. From 2015 on, however, the development appears to be rather "smooth".

Methodologically, it needs to be mentioned that the system boundaries had to be adapted slightly in the TBC case study. Instead of defining the spatial system boundaries based on products used in Germany, the use of aircrafts operated by German airlines has been used. Of course, these aircrafts as well operate outside of Germany and there are aircrafts of many non-German airlines that operate within Germany. Due to feasibility, however, the analysis has focused on aircrafts operated by German airlines.

Generally, the results for TBC should be well transferrable to other countries. Processes used in coating of the engine parts will be comparable in many countries as well as processes used in the removal of the coatings in maintenance. In fact, both –coating and maintenance– might be carried out by the same companies. Recovery of yttrium from EOL wastes is not practiced in any country. Some differences might occur concerning in-use dissipation. Particularly in sandy environments significantly higher in-use dissipation might occur. For a first rough estimation, the number of short-, mid-, and long-distance aircrafts and engines, respectively, could be used as a basis.

As described at the beginning of section 5.4, the other main field of application of TBC is stationary gas turbines accounting for about 35 % of the TBC market. To some extent, the results of this study can be transferred; waste treatment in F&M, maintenance, and at EOL can be assumed to be comparable. Differences need to be considered regarding lifespans and possibly in-use dissipation. Further information on TBC for stationary gas turbines can be found in (Zimmermann and Gößling-Reisemann 2014a; Zimmermann and Gößling-Reisemann 2014b).

5.5 Discussion of Modelling Approach and Data Uncertainties

Material stocks and flows including dissipative losses have been analyzed for three case studies following the methodological approach described in chapter 4. The methodological approach provides detailed insights to the occurrence, quantity, and type of dissipative losses along the product life cycle. Nevertheless, there are some limitations resulting from general data uncertainties and the modeling approach.

Quite generally, modeling results are only as reliable as the underlying data ("garbage in, garbage out"). To deal with the data uncertainties, for each case study, min and max parameter configurations have been analyzed, for the baseline scenario as well as the life cycle specific alternative scenarios. Hereby, data uncertainties regarding technical and non-technical parameters in the different

life cycle stages (e.g., material intensity or efficiencies in F&M, amount of products placed on the market in the use phase, collection rates and recycling efficiencies at EOL) as well as future developments of these parameters are covered. For each scenario this results in ranges of material flows and stocks defined by the respective min and max scenarios. Some parameter uncertainties influence the results significantly, and thus some significant differences between min and max scenarios can be observed. Future studies might be able to reduce some of these uncertainties by implementing more reliable data in the model. However, some uncertainties, including the future development, cannot be resolved entirely.

The material production stage showed some particular challenges regarding data availability. At least data could be obtained for the present situation of the main production routes of indium, gallium, and germanium from bauxite and zinc. To deal with the fact that only a fraction of bauxite and zinc ores is processed in routes suited for a recovery of the critical metal by-products, the system boundaries have been expanded. In this system expansion, all routes of processed zinc ores and bauxite have been included. This yields insights into the theoretically available as well as the lost amounts of indium, gallium, and germanium. By doing this, a more comprehensive assessment of losses in material production is achieved. If, for example, in the case of narrow system boundaries, a material is produced as a by-product from different ores in different process routes that vary in their efficiency, a significant reduction of dissipative losses (in a strict product-centric analysis) could be achieved, by shutting down all process routes for recovery of that by-product except the most efficient one. In fact, however, absolute dissipative losses of that metal are increased significantly as a complete dissipation occurs in the process routes that are located outside of the system boundaries. By expanding the system boundaries, this effect can be visualized. Due to data availability, this system expansion had to be limited to zinc blende ores and bauxite. Other potential sources of indium (e.g., roquesite, laforetite, indite), gallium (e.g., sphalerite, gallite, sohngeite), and germanium (e.g., coal ashes, cassiterite, hematite) could not be included. If the required data can be obtained in future studies, a more comprehensive assessment of the losses and potentials in the material production of these critical metals could be conducted. Regarding yttrium a similar approach has been chosen. However, the situation is slightly different, as yttrium is not produced as a by-product from one carrier metal. There are various potential sources comprising several REO. Due to lack of data, it has been assumed that higher losses occur from sources with a relatively low yttrium concentration if yttrium is recovered at all. The respective scenario therefore can be interpreted as a system expansion as conducted regarding the MP stage of the other metals.

Two further adjustments of the defined system boundary have been conducted. In the polymerization catalyst case study, a strict application of the defined system boundaries and modelling approach would have meant to cut-off everything after the germanium has dissipated into the PET. The decision to additionally cover the life cycle of the final-product (of the PET bottles) provided additional information on the material's fate as well as potential optimizations of the system. The other adjustment of system boundaries concerns the TBC case study. Instead of looking strictly at "prod-

ucts used in Germany" it has been decided to look at aircrafts operated by German airlines. This adjustment of the system boundaries has been motivated by reasons of feasibility.

Another uncertainty that regards all three case studies concerns the use of incineration residues (ashes, slags). The used data does not specifically refer to the actually considered waste streams but is rather generic; i.e., the actual use of the considered waste stream might differ from the assumptions in the model. Also, as briefly discussed in the respective case study sections, future changes in the use of ashes and slags are likely but have not been considered in the analysis due to lack of information and great uncertainties. Potential future changes may include a shift from use as construction material to landfilling or vice versa, as well as a further processing of incineration residues aiming at a recovery of selected critical metals.

Also modeling with lifespan distributions is connected with some challenges. When modelling material flows using lifespan distributions (other than SE/Dirac), past flows theoretically need to be considered back to the year the respective product has been initially introduced to the market, as even very long lifespans (i.e., $\gg T_{avg}$) have a probability greater than zero. In MFA, dealing with this problem is often impeded by data availability. In the analysis of the three presented case studies, this has been dealt with in different ways. In the CIGS case study, data reaching back to the initial market introduction has actually been available. Regarding the polymerization catalysts, a simplified approach has been taken due to the short lifespan of the considered end-product (PET bottles). Here, it has been assumed that products reach their EOL in the same year they have been placed on the market. In the TBC case study, a homogenous age distribution of the 2012 stock has been assumed. This approach might, however, lead to a slight overestimation of EOL flows within the first years of the considered timeframe. Generally, for products with annually increasing amounts placed on the market, cutting "very early" years off has only a minor influence on the results. When assuming a Weibull distribution, for example, with shape parameter values between $k = 2$ and $k = 5.6$, all years before $(T_1 - 1.5T_{avg})$ (with T_1 as the first year of the considered period in time) can be cut off, and still at least 95 % of the occurring material flows will be included, as demonstrated in (Zimmermann and Gößling-Reisemann 2014b).

Regarding the chosen approach for the parameter variation some aspects needs to be discussed, too. In the presented analysis, all parameters are varied individually in the different scenarios to make the influence of each parameter variation transparent. The model is entirely capable of combining all defined life cycle stage specific scenarios as desired, though. For example, it is possible to combine the most optimistic life cycle stage specific scenarios (in terms of dissipative losses) to obtain an optimistic scenario for the entire life cycle. Vice versa, a pessimistic life cycle wide scenario could be analyzed. In reality, there also might be dependencies between some of the parameters. Recycling rates, for example, might depend on waste amounts and cannot be increased independently (i.e., higher waste amounts may increase the feasibility of certain recycling processes in terms of economies of scale). Such interdependencies have not been considered in the analysis. Still, the model is very well capable of conducting the respective calculations. The connection of absolute waste

amounts and economic feasibility of recycling, for example, could be implemented by defining threshold values; only if the output flows from the use phase or the inputs to the EOL phase, respectively, exceed a certain amount, recycling will be practiced (e.g.,

$$If(Out_{Use} > 10{,}000kg),\ Then(R_{EOL} = 10\%), Else(R_{EOL} = 0)).$$

Also further refinements are imaginable. The condition might, for example, require that the output of the use phase exceeds a threshold value for several consecutive years before the recycling activity commences. Similar interconnections could be implemented for any parameters in the model, for example for the efficiency in F&M and the total amount of produced products (higher production amounts might allow for the use of more efficient F&M facilities).

6 CONCLUSIONS & OUTLOOK

The focus of this thesis is on presenting a concise definition of dissipative material losses, on refining the MFA methodology for the consideration of dissipation according to this definition, and on analyzing the flows of different critical metals (indium, gallium, germanium, and yttrium) along the life cycle of selected products (CIGS PV cells, polymerization catalysts, and thermal barrier coatings in aircraft engines). Thus, dissipative losses of the analyzed metals are quantified and classified, and weak spots and potential optimizations in the life cycle of the analyzed products are identified.

Quite generally, it can be said that the analysis of dissipative losses of materials can provide valuable knowledge required to achieve a more sustainable materials management. As described in section 2, global metal extraction and use have increased significantly in the past decades, including traditional mass metals like copper or iron as well as so-called critical metals such as REE, indium, gallium, germanium, and PGM. The growing dependency on a supply of these metals has triggered various criticality studies, assessing the importance and supply risks of various materials for different resource consuming systems (e.g., different countries, economic branches, federal states, etc.). Although the dependency on materials is well known, many materials including most metals are used in ways leading to significant dissipative losses along their life cycle. Although a relatively well working recycling infrastructure exists for some metals (mainly traditional mass metals or precious metals), even for these metals a significant share gets lost along their life cycle. Traditional mass metals such as iron, copper, or aluminum have comparably well working recycling systems, but still dissipative losses of 10 % to 50 % occur per product life cycle. These losses are not limited to product end-of-life and may occur at any stage of the product life cycle, depending on the type of application and processes applied in material production, and fabrication and manufacturing, as well as on the type of use. Regarding metals frequently considered to be critical such as indium, gallium, germanium, and REE (cf. section 2.1), a practically complete dissipation occurs along the product life cycle as a first screening study on dissipative losses of critical materials has shown (cf. section 3.1; Zimmermann and Gößling-Reisemann 2013). Considering issues such as criticality, scarcity, and environmental impacts of primary production, the relevance of this issue becomes obvious. Through dissipation material becomes unavailable in ways making a recovery unfeasible (cf. chapter 3), the dependence on supply of (probable scarce) resources increases, and production of new primary material is necessary. Vice versa, by reducing dissipative losses, the criticality of these metals can be reduced, scarce reserves can be protected, and by increasing recycling activities secondary material becomes available. The strict implementation of a closed-loop economy –which is the extreme case of a metal cycle without any dissipation– reduces environmental impacts not only by avoiding primary production through substitution by secondary materials but also by avoiding the release of potentially toxic and bioactive material into the environment, which is referred to as the double dividend of a circular economy. Different sustainable material management strategies have adopted these points, but usually on a rather ag-

gregated level (cf. section 2.3). So far, detailed knowledge about dissipation of critical metals is scarce, and existing SMM strategies are rather generic and little product-specific.

The more detailed the information on dissipative losses, the more specific optimizations can be developed. As most stages of the life cycle vary from product to product, optimizations are required to be product-specific. The required knowledge can be obtained by product-centric material flow analysis. However, so far, MFAs covering dissipative losses have mainly been conducted on material level and for bulk metals. Significantly fewer studies have been conducted for the "common critical metals" and only on an aggregated level. At the same time, a lack of consensus in nomenclature and consistent methodology can be identified (cf. chapter 3). Addressing this, a definition and a classification scheme for dissipative losses have been presented (cf. section 3.4) and implemented into the MFA methodology for retrospective and prospective product-centric dynamic analyses (cf. chapter 4). The detailed description of the methodological approach in this thesis[63] may facilitate similar studies in the future. The application of the methodological approach to the selected case studies returned various specific as well as more universal outcomes.

6.1 Outcome of the Case Studies

The methodological approach described in chapter 4 is applied to three case studies, indium and gallium in CIGS PV cells, germanium in polymerization catalysts, and yttrium in thermal barrier coating in aircraft engines, as described in chapter 5. In all three case studies the focus is on material flows related to products used in Germany; the considered timespan is 2012 to 2030. Details on the analyzed product systems as well as on adjustments of the system boundaries are given in chapter 5. In various scenarios, data uncertainties as well as alternating (future) developments are dealt with.

The screening study on dissipative losses of critical metals (Zimmermann and Gößling-Reisemann 2013) already indicates an almost complete loss of the analyzed metals on material level, which is confirmed in the thesis on the product level. In addition, information on quantity and type of dissipative losses could be obtained for each life cycle stage. In two case studies (polymerization catalysts and TBC) a complete dissipation can be observed; in one case study (CIGS) a major share of the analyzed metals dissipates along the product life cycle. In all analyzed case studies, the material production stage is a major hot spot regarding dissipation. In the CIGS and the TBC case study, fabrication and manufacturing appears to be another hot spot for dissipation. Insufficient or non-existent recycling in fabrication and manufacturing and at end-of-life further increases dissipation. In the polymerization catalysts case study, a complete dissipation in the use phase (of the catalyst) can be observed. In the expanded life cycle (i.e., the life cycle of PET bottles), the material dissipates further –almost exclusively at end-of-life– while a significant share also circulates within the system due to closed-loop (i.e., bottle-to-bottle) recycling. In the following, the key findings regarding dissipative losses

[63] A concise description of the methodological approach has also been published in (Zimmermann and Gößling-Reisemann 2015).

within the different life cycle stages of all three analyzed products are discussed together highlighting similarities as well as differences regarding the occurrence of dissipative losses.

Material production

The high scale of dissipative losses in the material production stage indicates that there is a great potential for a reduction of dissipation and an increase in production volumes for the considered critical metals. This aspect is particularly emphasized by the system expansion. Here, losses from process routes, in which the respective metals are not recovered, are included as well. This finding is rather contrary to the fact that the production of metals like indium, gallium, or germanium as by-products is sometimes described as an intrinsic problem regarding their availability (e.g., Wittmer 2011). It is argued that the production of the by-product can only be increased if the production of the carrier metal is increased. The analysis of the material production stage shows, however, that there is a significant potential –particularly in the processing of bauxite and zinc ores– to further increase the production of the by-products (and hereby reduce dissipative losses) without increasing the production of the carrier metal. Still, there seems to be a lack of economic incentives for further increases in the recovery. Future changes in the price of these metals might change this situation and increase economic incentives. As described in section 5.5, it needs to be considered that also in the scenario with expanded system boundaries, various ores and other raw materials (e.g., coal ashes) with significant concentration of the analyzed metals, are not considered. Considering these potential sources, too, would further increase the calculated dissipation from material production.

The dissipative losses from material production occur to a great extent outside of Germany. All losses directly related to mining occur in the respective countries: For all four analyzed metals, mining is to a large extent carried out in China (see metal profiles in section 5.1 for more detailed lists for each metal) where the related losses accumulate and potential improvements would have to be carried out. The next step of processing the mined ore –beneficiation– is commonly conducted in the same area, while the subsequent steps of smelting and refining can be located elsewhere. Here, a differentiation has to be made regarding the system boundaries. Strictly applying the defined system boundaries (material flows related to products used in Germany, i.e., considering only production routes in which the analyzed metals are recovered) indicates that dissipative losses of indium, germanium, and yttrium occur to a large extent in China and to a lesser extent in other countries outside of the EU. Only for gallium there is a domestic production from bauxite, which results in losses arising in Germany. If the system boundaries are expanded, though, –including losses from the general processing of the main carrier metals (bauxite and zinc ores)– the picture changes for indium and germanium. Both are produced as by-products from zinc production. Germany imports a significant amount of zinc concentrates (325 Gg in 2012, WVM 2013b) which are further processed to obtain pure zinc. However, there is no recovery of indium and germanium from these concentrates, resulting in dissipative losses occurring in Germany. Thus, potential optimization in the material production stage of indium, gallium, and germanium (e.g., modernizing facilities, installing additional recovery capacities for indium and germanium) could to some extent be implemented in Germany, although there ap-

pears to be a lack of economic incentives so far (R. Rodermund, pers. comm.). Only yttrium production is more or less completely limited to China where optimizations would have to be implemented.

Fabrication and manufacturing

The stage of fabrication and manufacturing is a major hot spot regarding dissipation for CIGS PV cells and TBC. In both case studies, the processes applied in F&M result in waste streams from which the contained critical metals are not (in case of yttrium) or only to some extent (in case of indium and gallium) recovered. In both cases, applying more efficient processes can reduce dissipation significantly, as also shown in the analyzed alternative scenarios. As recycling activities are at least for yttrium very unlikely, improving the process efficiency can be considered the main optimization measure for reducing dissipation in F&M. Geographically, F&M of PV cells –including CIGS– has shifted towards China in the past decade; in Germany only a few smaller companies produce CIGS, including for example Singulus Technologies AG and Avancis. The coating of turbine parts with TBC is partly conducted in Germany. The initial coating, however, is conducted at the sites of the turbine manufacturer, e.g. Rolls-Royce (UK), General Electric (U.S.), or Pratt and Whitney (U.S.). The F&M of polymerization catalysts as well as the F&M of PET bottles are very efficient and resulting dissipative losses can be considered negligible.

Use phase

Regarding in-use dissipation, the three case studies differ considerably. In the CIGS case study, there is no in-use dissipation at all, as it is a closed application. In the TBC case study, there are minor losses in the use phase during aircraft operations to the environment. These losses are dispersed over a wide area –depending on the flight path– and a targeted recovery is hardly imaginable. In addition there are dissipative losses from maintenance of the coated turbine parts. In maintenance, the coating is removed and the parts are re-coated. While the re-coating is allocated to F&M, the disposal of the removed coating is considered to be a part of the use phase. Here, the contained yttrium is lost due to lack of recycling. For German airlines, this step is to a large extent carried out in Germany (e.g., for the biggest German airline Lufthansa at different Lufthansa Technik sites). As described, there is no economic incentive to recover yttrium from the waste stream, and future changes are unlikely.

Contrary to the other case studies, a complete dissipation (into another material flow) occurs in the use phase of the polymerization catalysts. This dissipation appears to be an accepted loss within the production of PET. No changes are indicated here –except the substitution by other catalyst material, which would then dissipate instead. This dissipation occurs in the country in which the PET is produced, which is done in many different countries all over the globe –about 24 % is produced in China, 20 % in the EU, 20 % in Canada, Mexico, and the U.S., and 16 % in the rest of Asia (cf. PlasticsEurope 2013). A system expansion is conducted in the polymerization catalyst case study and the “expanded life cycle” includes the further fate of the PET –the F&M of PET bottles, their use in Germany, and

their end-of-life. Further in-use dissipation from the PET bottles to the contained beverage occurs only in a marginal scale.

End-of-life

At EOL, for all three analyzed products dissipation occurs mostly in Germany. For the CIGS cells, it seems rather likely that recycling activities for EOL CIGS PV cells will be initiated in the future. By doing this, dissipation from EOL can be reduced significantly as shown in the respective scenario. In reality, however, EOL flows of CIGS PV cells will have to exceed a certain threshold to enable economic feasible recycling activities as discussed in section 5.2.7.

Regarding polymerization catalysts, the expanded life cycle needs to be considered. Here, further dissipation occurs from PET bottles that are not recycled in a closed-loop but in an open-loop (resulting in further dissipation to other material flows) or incinerated. In any case, there is no recovery of germanium and future changes are unlikely due to a lack of economic (and ecological) feasibility. A significant reduction of further dissipation can be achieved, though, by increasing the share of closed-loop recycling. A similar effect could be achieved by increasing the share of refillable bottles instead of one-way bottles. Refillable bottles are significantly more resource efficient, i.e., every bottle transports a fifteen-fold amount of beverage before being recycled. Hereby, the absolute material flows including the dissipative losses are reduced. Regarding thermal barrier coatings, there are no recycling activities for yttrium at EOL, and future changes are unlikely, mainly due to economic reasons.

Types of dissipative losses

Besides the life cycle stages, dissipative losses have been differentiated according to the receiving media –environment, other material flows, and landfills. In all three analyzed case studies, dissipation into the environment plays only a minor role (i.e., <2 % of cumulative dissipative losses (CDL) in the baseline scenarios). The largest part of the CDL is split between other material flows and landfills. In the CIGS case study, the majority of dissipative losses accumulate on landfills (about 70 % to 77 % in the baseline scenario). In the TBC case study, the distribution is closer to an even split (in the baseline scenarios about 42 % to 45 % to landfills and 54 % to 57 % to other material flows). In the polymerization catalyst case study, the majority of dissipative losses go to other material flows (in the baseline scenario about 81 %). Table 76 summarizes the cumulative dissipative losses to other material flows and landfills for the baseline scenarios for all three case studies.

Table 76: Cumulative dissipative losses to other material flows and landfills (referring to baseline scenarios; 2012-2030); percentages indicate share of total cumulative losses

Case study / metal	Other material flows	Landfills
CIGS / indium	933 – 44,186 kg (22 - 29 %)	2,301 – 154,606 kg (70 – 77 %)
CIGS / gallium	376 – 32,558 kg (22 – 29 %)	927 – 113,920 kg (70 – 77 %)
Polymerization cats. / germanium	4,575 – 14,217 kg (81 %)	1,018 – 3,158 kg (18 %)
TBC / yttrium	6,108 – 11,280 kg (54 – 57 %)	5,004 – 8,179 kg (42 – 45 %)

Regarding the dissipative losses to other material flows, it needs to be mentioned that a significant share of these losses consists of slags, ashes, etc. used as filling or construction material. This is a special case of dissipation to other material flows compared to, e.g., contamination of one material by another. This aspect is discussed in more detail in section 6.2.

Summary: Recommended actions for reducing dissipation

Based on the case study results (see chapter 5, particularly sections 5.2.7, 5.3.6, and 5.4.6) and following the previous sections, different actions for reducing dissipation can be recommended for the different life cycle stages of the analyzed products. These actions are summarized for CIGS PV cells in Table 77, for polymerization catalysts in Table 78, and for thermal barrier coatings in Table 79. In addition, the actions have been discussed regarding their feasibility, and the geographic scope of the action has been noted in the tables. A noteworthy aspect is that the most feasible actions for reducing dissipation do to a large extent not concern material recycling but optimizations of other parts of the life cycle (e.g., F&M) or systemic optimizations of the EOL stage (in case of polymerization catalysts/ PET bottles). Considering that the discussion on critical metals focuses rather narrowly on the recycling situation (e.g., Hagelüken 2014; Rademaker, Kleijn, and Yang 2013; Buchert et al. 2012; Buchert, Schüler, and Bleher 2009), this can be considered a rather remarkable finding.

Table 77: Recommended actions for reducing dissipative losses along the life cycle of CIGS PV cells

Life cycle stage	Recommended actions for reducing dissipation	Discussion of action & comments
MP	Increase recovery of In and Ga as by-products in processing of zinc ores and bauxite.	Subject to price development; constantly higher prices required to provide necessary economic incentives; in case of indium more likely considering scarcity of indium. Geographic scope: Mining mainly located in China, further processing of zinc concentrates in bauxite also in Germany.
F&M	Improve process efficiency. Improve recycling of F&M waste.	Possible and likely to be implemented as more efficient processes already exist on lab scale. Geographic scope: F&M is shifting to other countries, particularly to China, and to a shrinking extent carried out in Germany.
EOL	Improve recycling situation by recycling quotas, development of technologies, and their implementation.	Possible and likely to be implemented; several publicly funded research projects have been initiated in the past years. Geographic scope: Germany and neighboring countries.

Table 78: Recommended actions for reducing dissipative losses along the (expanded) life cycle of polymerization catalysts

Life cycle stage	Recommended actions for reducing dissipation	Discussion of action & comments
MP	Increase recovery of Ge as by-product in processing of zinc ores –and potentially from other sources.	Subject to price development; constantly higher prices required to provide necessary economic incentives. Geographic scope: Mining mainly located in China, further processing of zinc concentrates also in Germany.
EOL	Increase B2B recycling.	Current trends indicate a contrary development. However, examples from the past showed that the German legislature is less hesitant regarding political interventions on packaging (e.g., refund policy) than in other areas. Given the political intent, optimizations could be rather easily achieved. Geographic scope: Germany
	Increase use of refillable bottles.	Again, current trends indicate a contrary development; just recently Coca Cola Germany announced to significantly increase the use of one-way bottles (Deutsche Umwelthilfe e.V. 2015). Again, political inventions by, e.g. adapting the refund policy, could be achieved relatively easy. Geographic scope: Germany

Table 79: Recommended actions for reducing dissipative losses along the life cycle of thermal barrier coatings

Life cycle stage	Recommended actions for reducing dissipation	Discussion of action & comments
MP	Increase efficiency in yttrium recovery.	Future price increases might trigger improvements. Geographic scope: Mainly China.
F&M	Increase efficiency of coating processes.	Already efficiencies seem to vary quite a bit between the different manufacturers, and processes that could reduce dissipative losses significantly are already available. However, economic incentives are not particularly pronounced, and expert information indicates that improving the efficiency in the F&M stage and improving recovery & recycling has a low priority. Geographic scope: Germany
EOL	Initiate EOL recycling activities.	Rather unlikely due to lack of economic incentives. Geographic scope: Germany

Integration of actions into existing SMM strategies

In section 2.3, the elements of various existing SMM strategies have been described. Although the elements described in these strategies are rather generic, the recommendations given regarding the analyzed products can be sorted accordingly, as shown in Table 80.

Table 80: Matching of SMM strategy elements and recommended actions

SMM strategy element (cf. section 2.3)	Matching recommended action (cf. Table 77,Table 78, and Table 79; and sections 5.2.7, 5.3.6, and 5.4.6)	Concerned	
		product	life cycle stage
Increase material efficiency in supply chains	Increase efficiency in MP and F&M.	CIGS, TBC	MP, F&M
Incentivize consumer behavior	Increase closed-loop (B2B) recycling; increase use of refillable bottles.	PET bottles (expanded life cycle of p.c.)	Use phase, EOL
Develop more efficient recycling processes	Initiate recycling activities; increase recycling of waste from F&M and EOL.	CIGS, TBC	F&M, EOL
Environmental tax reforms that incentivize recycling			
Defining waste treatment and recycling targets			
Increase producer responsibility	Increase recycling; increase process efficiency.	CIGS, TBC	F&M, EOL

In addition, some further recommendations, which could result in additional reductions of dissipative losses along the life cycle of the analyzed products, can be obtained by reviewing the elements of SMM strategies in section 2.3. An important element which can be found in many SMM strategies is the increase of the product durability, i.e., an increase of the product service lifespan. The product service lifespan has been adapted in the model in the preparation of the min and max scenarios, but it has not been varied separately in the scenario analysis. Thus, the influence of increasing the product durability has not been quantified; however, the influence can be easily explained qualitatively: Increasing the product durability or the service lifespan, respectively, directly reduces the material demand by reducing the replacement of products from the in-use stock. Assuming an unaltered in-use stock, all upstream and downstream material flows including dissipation are reduced. Another element within many SMM strategies is eco-design of products, i.e., designing products with reduced mass and better recyclability. This element is particularly generic, and its adaption has to be very application-related and specific. Quite generally, the benefit of eco-design is evident, though. Reducing product mass reduces all material flows along the product life cycle (assuming that F&M efficiencies remain unaltered), and an increased recyclability reduces dissipative losses from EOL. An element which can also be found in many SMM strategies is the phase-out of landfilling, i.e., the complete recycling, incineration of waste, or down-cycling of waste (i.e., use as construction or filling material of waste and incineration residues). Regarding the analyzed case studies, the phase-out of landfilling would most likely not result in an increase in recycling but a further increased dissipation to other material flows by use of waste material for, e.g. construction purposes. As dissipation to landfills and other material flows are the major types of dissipation in the analyzed case studies, the question arises if there is a potential for recovering these losses. This question is considered in the discussion on landfill and urban mining.

Landfill and urban mining

A significant share of dissipative losses (from all three case studies) goes to landfills. In Europe, there are between 150,000 and 500,000 historic and still active landfills (Jones et al. 2013). Thus, it makes sense to take a closer look at the possibility to recover the materials of interest from landfills. In the past years, there have been various projects investigating the feasibility and potential of landfill mining activities. Landfill mining can be defined as "*a process for extracting materials or other solid natural resources from waste materials that previously have been disposed of by burying them in the ground*" (Krook, Svensson, and Eklund 2012). For quite some time, the focus in research on landfills has been on solving issues such as lack of landfill space and local pollution concerns while recycling efforts have played a secondary role. Since a couple of years, a new perspective on landfill mining is taken, though, seeing landfills as valuable reservoirs for resource extraction instead of major costs to society and contributors to global warming and groundwater pollution (Jones et al. 2013; Krook, Svensson, and Eklund 2012). Still, many aspects, in particular regarding the recovery of critical metals, remain unclear. In a screening on landfill mining potentials, Quaghebeur et al. (2013) state that there are significant differences in the material composition, depending on the age of the landfill, the type of the landfill, the country or region where the landfill is located, and the period the waste was landfilled. Furthermore, most studies on landfill mining focus on mass metals –including copper, chromium, nickel, and zinc–, plastics, paper and cardboard, wood, and textiles, while the recovery of low concentrated materials including critical metals is seen rather problematic due a probable lack of economic feasibility (Jones et al. 2013; Quaghebeur et al. 2013).

Binnemans et al. (2013a) see a substantial potential for recovery of REE from landfills, without presenting any supporting details, though. In (Binnemans et al. 2013b) it is said that although the concentration of REE in landfills is much lower than in EOL products, the volumes are enormous and the total amount of REE is very large. This can also be supported by the results of the case study on yttrium in thermal barrier coatings. The waste of material production of REE is often dumped in tailing ponds close to the mine or processing plant. The concentration in these residues are rather high, so these tailings can be considered as attractive REE deposits (Binnemans et al. 2013b). An analysis of tailings from Mountain Pass in the U.S. showed REO concentrations between 3 % and 5 % (Binnemans et al. 2013b). Along the further life cycle, dilution of REE in most types of slags remains a problem and further research on the fate of REE and potential ways for recovery is required (Binnemans et al. 2013b). Especially compared to primary REE sources, the concentration in EOL waste streams such as slags is low, and existing processes are not suited for an economic recovery.

Summarizing, it can be concluded that a recovery of critical metals from landfills is currently technologically and economically unfeasible; changes are scarcely to be expected soon. Partly, though, the unfeasibility is caused by a lack of knowledge regarding the composition of landfills. Here, MFA studies can provide valuable knowledge to support landfill mining activities and studies in the future. Besides quantifying the amount of material dissipating to landfills, tracking the dissipative losses geographically would increase the value of the information significantly.

Closely related to landfill mining is the concept of urban mining. Although sometimes both terms are used synonymously, landfill mining exclusively focuses on landfills while urban mining has a much broader scope including long-living infrastructure and other anthropogenic stocks, too. It may be defined as "*the systematic reuse of anthropogenic materials from urban areas*" (Brunner 2011). With regard to the analyzed case study, the dissipation of critical metals in slags and ashes used as construction and filling material in long-living infrastructure is of particular interest regarding urban mining. As with landfill mining, a recovery of critical metals from long-living infrastructure is currently technologically and economically unfeasible. However, again, MFA studies can provide valuable knowledge to support urban mining activities and studies in the future by quantifying stocks, uncovering stock compositions and secondary material flows as well as their potential recoverability, etc.

6.2 Methodological Consideration

Several methodological aspects including data uncertainties and availability have already been discussed in section 5.5. This includes the parameter variation and scenario analysis, the expansion and adjustment of system boundaries, and challenges related to modelling with lifespan distributions. Further aspects including the transferability of the results have been discussed in the discussions sections of the case studies. Against this background, only some selected methodological aspects will be discussed briefly in the following including the classification scheme for dissipative losses, the CDL as an aggregated indicator, and probable future methodological expansions.

Classification of dissipative losses

In the methodological approach used in this work, dissipative losses have been differentiated according to the classification scheme presented in section 3.4. As described, dissipation in general is defined based on the change in the material's availability which is understood as the material recovery becoming unfeasible. For each life cycle stage the arising dissipative losses are classified according to the receiving medium: the environment, other material flows, and landfills. Although the recovery of material which has dissipated into these media can be considered unfeasible today, a further qualitative differentiation of the theoretic feasibility of recovery is possible. A material which has dissipated into the environment is usually widely dispersed in particularly low concentrations, and a targeted recovery –even if energy demand and expenditure of time and labor are not an issue– is hardly possible. For dissipative losses to landfills, a theoretic possibility for recovery exists (by landfill mining) as argued in section 3.4 as well as in section 6.1. For dissipative losses to other material flows there is also a theoretical possibility for recovery when the "carrier product" reaches its end-of-life. In the analyzed case studies, however, the majority of dissipative losses to other material flows consist of ashes, slags, etc. which are used as construction or filling material. This is a special case of dissipative losses to other material flows which is located somewhat between dissipation to landfills and dissipative losses to other material flows in "mobile applications". Quantifying these two types of dissipation separately could provide additional valuable information, e.g. as a basis for studies on urban

mining potentials, and should be considered as a possible expansion of the methodological approach and underlying classification scheme in the future.

In addition to the differentiation of dissipative losses according to the three receiving media, the cumulative dissipated losses –CDL– have been used as an aggregate indicator for interpreting the results and comparing the different scenarios. Instead of looking at at least three different categories of results, the CDL facilitates a first comparison of different scenarios. Although some specifics and details are disregarded when working with aggregate indicators, deriving general conclusions can be significantly streamlined. Particularly for policy making, a growing demand for aggregate indicators in environmental research can be observed (e.g., Giljum et al. 2011; Jollands, Lermit, and Patterson 2003). For material dissipation, the CDL could fulfill this demand. However, for deriving measures and actions for optimization etc. the detailed results need to be considered.

Methodological expansions: hazard and exposure assessment

The methodological approach used in this study focuses on assessing losses of material against the background of resource conservation and sustainable materials management; i.e. material flows are assessed with consideration of their availability and potential for recovery for use in other applications. The approach is, however, closely related to some approaches used for the analysis and assessment of the release of chemicals and other potentially toxic substances to environmental compartments; these approaches aim at estimating potential environmental risks in terms of hazard and exposure. In particular, the analysis of releases of engineered nanomaterials (ENM) has received a lot of attention in the past years. Examples and more details on different methodological approaches used for exposure assessment can be found, for example, in (Wigger et al. 2015; Gottschalk, Sun, and Nowack 2013; Gottschalk et al. 2010; Gottschalk, Scholz, and Nowack 2010).

Although the metals analyzed in this thesis are not particularly toxic (the salts of indium, gallium, germanium, and yttrium have a low toxicity; Emsley 2011), combining the methodological approaches could make sense for future studies of materials that are known to be critical as well as toxic such as antimony, or of materials whose toxicity is unknown, which is the case for many ENM. Thus, combining the presented approach with approaches for exposure assessment appears to be an interesting object for future research.

Methodological expansions: geographic tracking of dissipative losses

As described, the results from this thesis –and possible future studies following the same methodological approach– can be used to serve as a basis for landfill and urban mining studies. To support this, the method could be supplemented by geographic information on the material flows by combining the material flow model with a geographic information system (GIS). A review of the functionality of modern GIS, their potential role in urban mining studies, and their possible combination with MFA models and data has been published recently by Zhu (2014). By combining MFA models with GIS, valuable information on the location and distribution of recyclable resources can be obtained, facilitating future recovery activities (i.e., urban and landfill mining activities) considerably. However, data

availability and accessibility remain major challenges in this endeavor (Zhu 2014). To solve this issue, Zhu (2014) recommends to develop specific national spatial data bases to support urban mining.

Besides urban and landfill mining, geographic information can also be valuable regarding optimizations of the different life cycle stages. By adding information on the involved countries or regions for each life cycle or process stage –as it has been done in section 6.1–, it can be highlighted where the recommended actions for reducing dissipation have to be carried out, and –based on this– the responsible stakeholders can be identified. Adding this information requires significantly less information than combining the MFA model with high-resolution GIS, and can usually be done based on the data already collected and implemented in the MFA model.

6.3 Outlook: Objects for Future Research

Various possible objects for future research arise from this thesis as discussed in the previous sections as well as in the conclusions sections of the case study analysis in chapter 5 and summarized in the following.

The quality of the case study results could be further increased if additional data particularly for material production, but also for F&M (e.g., data on metal concentrations in CIGS PV cells) could be obtained. More differentiated scenarios could be analyzed easily, using the already available data and model (e.g., analyzing best or worst case scenarios for each product). The case study results could also be upscaled to a larger geographical area or transferred to other regions or countries by including additional data. The case study results can also serve as a basis for more comprehensive MFA studies of indium, gallium, germanium, and yttrium, comprising other applications as well. Likewise, the approach could be used to analyze the flows of other materials along the life cycle of other products. In the context of future studies of dissipative losses and potential optimizations, also economic consequences could be highlighted in more details.

The expansion of the classification scheme for dissipative losses to further differentiate the dissipative losses to other material flows (considering dissipative losses to ashes and slags used as filling or construction material as a separate type of dissipation) as well as the combination of the MFA model with geographic information systems would provide a detailed map of dissipative losses and could facilitate future urban and landfill mining studies significantly. Combining the presented methodological approach with methods for exposure assessment would provide further information particularly relevant for known toxic substances and ENM.

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APPENDIX

In the following sections, additional data and the full results of the three case studies are given. For each analyzed scenario, the results are presented in a table comprising all major flows as well as in-use stocks and accumulated dissipative losses.

Appendix A) CIGS photovoltaics

Data

Table A 1: Time series of PV and CIGS installations

Scenario	Installed Capacity, all PV technologies		CIGS share		Annual PV installations		CIGS installations	
Year	Min scenario [MW]	Max scenario [MW]	Continuity	Thin-film renaissance	Min scenario [MW]	Max scenario [MW]	Min scenario [MW]	Max scenario [MW]
1990	2	2			2.00	2.00	0	0
1991	2	2			0.00	0.00	0	0
1992	6	6			4.00	4.00	0	0
1993	9	9			3.00	3.00	0	0
1994	12	12			3.00	3.00	0	0
1995	18	18			6.00	6.00	0	0
1996	28	28			10.00	10.00	0	0
1997	42	42			14.00	14.00	0	0
1998	54	54	0.05%	0.05%	12.00	12.00	0.01	0.01
1999	70	70	0.10%	0.10%	16.00	16.01	0.02	0.02
2000	114	114	0.15%	0.15%	44.00	44.01	0.07	0.07
2001	176	176	0.20%	0.20%	62.01	62.02	0.12	0.12
2002	296	296	0.20%	0.20%	120.01	120.03	0.24	0.24
2003	435	435	0.60%	0.60%	139.02	139.05	0.83	0.83
2004	1105	1105	0.40%	0.40%	670.03	670.08	2.68	2.68
2005	2056	2056	0.20%	0.20%	951.05	951.12	1.90	1.90
2006	2899	2899	0.20%	0.20%	843.07	843.19	1.69	1.69
2007	4170	4170	0.50%	0.50%	1271.11	1271.30	6.36	6.36
2008	10566	10566	1.00%	1.00%	6396.18	6396.47	63.96	63.96
2009	17944	17944	1.70%	1.70%	7378.29	7378.75	125.43	125.44
2010	25429	25429	1.17%	1.17%	7485.46	7486.21	87.58	87.59
2011	33033	33033	1.32%	1.32%	7604.76	7605.97	100.38	100.40
2012	36337	36337	0.75%	0.75%	3305.26	3307.27	24.79	24.80
2013	36697	39874	0.91%	1.65%	361.66	3542.33	3.30	58.32
2014	37056	43411	1.07%	2.54%	363.09	3546.07	3.89	90.16
2015	37416	46948	1.23%	3.44%	365.44	3552.19	4.51	122.15
2016	37775	50484	1.40%	4.34%	369.13	3561.85	5.15	154.41
2017	38135	54021	1.56%	5.23%	374.73	3576.57	5.83	187.10
2018	38494	57558	1.72%	6.13%	382.95	3598.22	6.58	220.48
2019	38854	61095	1.88%	7.02%	394.61	3629.08	7.41	254.90
2020	39213	64632	2.04%	7.92%	410.69	3671.84	8.38	290.81
2021	39573	68169	1.97%	8.66%	432.28	3729.52	8.52	323.01
2022	39933	71705	1.90%	9.40%	460.60	3805.48	8.77	357.79
2023	40292	75242	1.84%	10.14%	496.98	3903.23	9.12	395.90
2024	40652	78779	1.77%	10.88%	542.80	4026.30	9.60	438.22
2025	41011	82316	1.70%	11.63%	599.50	4177.99	10.19	485.69
2026	41371	85853	1.63%	12.37%	668.43	4361.01	10.91	539.28
2027	41730	89390	1.56%	13.11%	750.88	4577.06	11.74	599.92
2028	42090	92926	1.50%	13.85%	847.85	4826.42	12.68	668.36
2029	42449	96463	1.43%	14.59%	960.03	5107.40	13.71	745.12
2030	42809	100000	1.36%	15.33%	1087.60	5415.89	14.79	830.26

Results

In the following, the full results for all analyzed scenarios are presented. The parameters are explicated in the following table.

Table A 2: Abbreviations and notations of stocks and flows used in CIGS case study

Flow	Parameter
Input flows in material production (environment to technosphere)	In_{MP}
Dissipative losses from F&M to landfills	$L_{F\&M,LF}$
Dissipative losses from use phase to environment	$L_{Use,Env}$
Dissipative losses from use phase to other material flows	$L_{Use,omf}$
Dissipative losses from use phase to landfills	$L_{Use,lf}$
Dissipative losses from EOL to environment	$L_{EOL,env}$
Dissipative losses from EOL to other material flows	$L_{EOL,omf}$
Dissipative losses from EOL to landfills	$L_{EOL,lf}$
Recycled material from F&M	$R_{F\&M}$
Recycled material from EOL	$R_{F\&M,EOL}$
Input flow to F&M / material demand	$Out_{MP} = In_{FM}$
Input flow to use phase	$Out_{FM} = In_{Use}$
Input flow to EOL phase	$Out_{Use} = In_{EOL}$
Dissipative losses from material production to environment	$L_{MP,env}$
Dissipative losses from material production to other material flows	$L_{MP,omf}$
Dissipative losses from material production to landfills	$L_{MP,lf}$
Dissipative losses from F&M to environment	$L_{F\&M,env}$
Dissipative losses from F&M to other material flows	$L_{F\&M,omf}$
In-use stock	$Stock_{Use}$
Cumulative recycled material (cumulative, starting from 2012)	$\sum R$
Cumulative dissipative losses to other material flows (cumulative, starting from 2012)	$\sum L_{LF}$
Cumulative dissipative losses to landfills (cumulative, starting from 2012)	$\sum L_{OMF}$
Cumulative dissipative losses to environment (cumulative, starting from 2012)	$\sum L_{Env}$

Results: Indium

Table A 3: Results – CIGS PV Cells – Indium – Baseline-Scenario – Min

Baseline-Scenario - Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1325.9	166.3	185.2	201.8	216.7	230.3	243.4	256.7	270.9	256.7	245.4	236.6	229.9	224.7	220.4	216.4	212.0	206.5	199.1
$L_{F\&M,LF}$	25.9	3.1	3.4	3.5	3.6	3.7	3.8	3.8	3.8	3.5	3.2	2.9	2.7	2.5	2.3	2.2	2.0	1.8	1.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.1	0.2	0.4	0.7	1.1	1.7	2.6	3.8	5.3	7.2	9.7	12.6	16.2	20.4	25.2	30.8	36.9
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.4	0.6	0.8	1.1	1.4	1.8	2.3	2.8	3.4	4.1
$R_{F\&M}$	113.5	14.9	17.3	19.6	21.8	24.0	26.2	28.4	30.8	30.0	29.3	28.9	28.6	28.5	28.5	28.4	28.2	27.8	27.2
$R_{F\&M,EOL}$	0.0	0.1	0.2	0.3	0.6	1.0	1.7	2.8	4.2	6.3	9.1	12.9	17.7	23.9	31.6	41.0	52.3	65.7	81.4
$Out_{MP} = In_{FM}$	729.2	92.0	103.0	112.8	121.8	130.2	138.4	146.7	155.6	148.3	142.5	138.1	134.9	132.5	130.7	129.0	127.0	124.3	120.5
$Out_{FM} = In_{Use}$	357.0	45.8	52.1	58.0	63.6	69.0	74.5	80.2	86.3	83.5	81.4	80.0	79.2	78.9	78.9	78.9	78.7	78.1	76.7
$Out_{Use} = In_{EOL}$	0.1	0.1	0.3	0.5	1.0	1.8	2.9	4.7	7.1	10.5	15.0	20.9	28.5	37.9	49.6	63.7	80.4	99.9	122.3
$L_{MP,env}$	13.3	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0
$L_{MP,omf}$	13.3	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0
$L_{MP,lf}$	570.1	71.1	78.7	85.3	91.0	96.2	101.0	105.9	111.1	104.6	99.4	95.2	92.0	89.3	87.1	84.9	82.7	80.0	76.7
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	232.9	28.2	30.2	31.7	32.7	33.4	33.9	34.3	34.6	31.3	28.6	26.3	24.3	22.5	21.0	19.5	18.0	16.5	15.0
$Stock_{Use}$	6501.4	6547.0	6598.9	6656.3	6718.9	6786.2	6857.8	6933.3	7012.5	7085.5	7151.9	7210.9	7261.7	7302.7	7332.0	7347.2	7345.6	7323.8	7278.1
$\sum R$	113.6	128.5	146.0	165.9	188.3	213.3	241.2	272.4	307.5	343.8	382.2	424.0	470.4	522.9	582.9	652.3	732.8	826.4	934.9
$\sum L_{OMF}$	246.1	276.0	308.1	341.8	376.9	413.0	450.0	488.0	527.3	564.4	600.0	635.2	670.6	707.2	745.8	786.9	831.3	879.7	932.5
$\sum L_{LF}$	596.0	670.2	752.3	841.1	935.8	1035.7	1140.7	1250.6	1365.7	1474.3	1577.4	1676.4	1772.1	1865.3	1956.5	2045.9	2133.4	2218.6	2301.1
$\sum L_{Env}$	13.3	14.9	16.6	18.5	20.4	22.4	24.4	26.5	28.6	30.5	32.3	33.9	35.5	36.9	38.2	39.5	40.7	41.8	42.8

Table A 4: Results – CIGS PV Cells – Indium – Baseline-Scenario – Max

Baseline-Scenario - Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	2275.7	5134.4	7617.5	9902.7	12009.5	13959.6	15777.5	17491.1	19131.4	20367.4	21617.2	22913.0	24286.2	25765.2	27372.8	29122.5	31015.0	33035.0	35147.9
$L_{F\&M,LF}$	44.4	96.6	138.2	172.9	201.6	225.1	244.2	259.4	271.5	276.3	279.9	282.7	285.0	287.2	289.3	291.2	292.8	293.8	293.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.4	0.9	1.6	2.9	4.8	7.6	11.6	17.1	24.5	34.3	46.9	62.7	82.4	106.4	135.1	168.8	207.7
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.8	1.3	1.9	2.7	3.8	5.2	7.0	9.2	11.8	15.0	18.8	23.1
$R_{F\&M}$	194.9	460.0	711.7	962.1	1209.9	1454.7	1696.7	1936.9	2177.1	2377.3	2583.3	2798.6	3026.8	3271.5	3535.5	3820.8	4127.3	4452.9	4792.4
$R_{F\&M,EOL}$	0.1	0.3	0.6	1.3	2.5	4.4	7.5	12.2	19.0	28.8	42.5	61.1	86.0	118.7	160.7	213.9	280.0	360.8	458.1
$Out_{MP} = In_{FM}$	1251.6	2839.6	4236.2	5537.3	6752.0	7891.1	8966.9	9994.2	10989.9	11762.2	12550.0	13372.3	14247.9	15194.3	16226.0	17352.1	18574.5	19885.2	21264.5
$Out_{FM} = In_{Use}$	612.7	1413.2	2142.8	2846.2	3525.7	4184.9	4828.7	5463.5	6097.6	6622.1	7168.1	7747.0	8370.6	9050.8	9797.8	10619.5	11519.3	12494.6	13534.8
$Out_{Use} = In_{EOL}$	0.2	0.5	1.1	2.3	4.3	7.6	12.8	20.6	31.9	47.8	69.8	99.2	138.1	188.4	252.3	332.1	430.1	548.4	688.8
$L_{MP,env}$	22.8	49.9	71.9	90.8	106.8	120.2	131.5	140.9	148.8	152.8	156.1	159.1	161.9	164.6	167.3	169.9	172.3	174.4	175.7
$L_{MP,omf}$	22.8	49.9	71.9	90.8	106.8	120.2	131.5	140.9	148.8	152.8	156.1	159.1	161.9	164.6	167.3	169.9	172.3	174.4	175.7
$L_{MP,lf}$	978.5	2195.0	3237.4	4183.9	5044.0	5828.1	6547.7	7215.1	7843.9	8299.7	8755.0	9222.5	9714.5	10241.7	10812.3	11430.6	12095.8	12801.1	13531.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	399.7	869.8	1243.5	1556.1	1814.8	2026.3	2197.4	2334.4	2443.7	2486.5	2518.7	2544.0	2565.4	2584.9	2603.4	2620.7	2635.1	2644.0	2643.5
$Stock_{Use}$	10742.5	12155.1	14296.8	17140.7	20662.1	24839.3	29655.2	35098.1	41163.8	47738.1	54836.5	62484.3	70716.8	79579.1	89124.6	99412.0	110501.2	122447.4	135293.4
$\sum R$	195.0	655.3	1367.7	2331.1	3543.5	5002.6	6706.7	8655.8	10851.8	13257.9	15883.7	18743.4	21856.2	25246.4	28942.6	32977.3	37384.6	42198.3	47448.7
$\sum L_{OMF}$	422.5	1342.4	2658.3	4306.1	6229.3	8378.7	10712.3	13195.2	15799.4	18455.8	21155.2	23892.6	26666.8	29479.1	32332.2	35229.2	38171.7	41158.9	44185.8
$\sum L_{LF}$	1023.0	3314.6	6690.2	11047.2	16293.0	22346.6	29138.9	36614.2	44730.9	53308.8	62346.4	71855.4	81860.1	92396.0	103506.6	115240.2	127643.9	140757.5	154606.2
$\sum L_{Env}$	22.8	72.7	144.6	235.4	342.1	462.4	593.8	734.7	883.5	1036.3	1192.4	1351.5	1513.4	1678.0	1845.3	2015.2	2187.5	2361.9	2537.6

Table A 5: Results – CIGS PV Cells – Indium – Material production alternative (Scenario A) – Min

Material production alternative (Scenario A) - Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1121.9	140.7	156.7	170.7	183.3	194.9	206.0	217.2	229.2	217.2	207.7	200.2	194.5	190.1	186.5	183.1	179.4	174.7	168.5
$L_{F\&M,LF}$	25.9	3.1	3.4	3.5	3.6	3.7	3.8	3.8	3.8	3.5	3.2	2.9	2.7	2.5	2.3	2.2	2.0	1.8	1.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.1	0.2	0.4	0.7	1.1	1.7	2.6	3.8	5.3	7.2	9.7	12.6	16.2	20.4	25.2	30.8	36.9
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.4	0.6	0.8	1.1	1.4	1.8	2.3	2.8	3.4	4.1
$R_{F\&M}$	113.5	14.9	17.3	19.6	21.8	24.0	26.2	28.4	30.8	30.0	29.3	28.9	28.6	28.5	28.5	28.4	28.2	27.8	27.2
$R_{F\&M,EOL}$	0.0	0.1	0.2	0.3	0.6	1.0	1.7	2.8	4.2	6.3	9.1	12.9	17.7	23.9	31.6	41.0	52.3	65.7	81.4
$Out_{MP} = In_{FM}$	729.2	92.0	103.0	112.8	121.8	130.2	138.4	146.7	155.6	148.3	142.5	138.1	134.9	132.5	130.7	129.0	127.0	124.3	120.5
$Out_{FM} = In_{Use}$	357.0	45.8	52.1	58.0	63.6	69.0	74.5	80.2	86.3	83.5	81.4	80.0	79.2	78.9	78.9	78.9	78.7	78.1	76.7
$Out_{Use} = In_{EOL}$	0.1	0.1	0.3	0.5	1.0	1.8	2.9	4.7	7.1	10.5	15.0	20.9	28.5	37.9	49.6	63.7	80.4	99.9	122.3
$L_{MP,env}$	11.2	1.4	1.5	1.6	1.6	1.7	1.7	1.7	1.8	1.6	1.5	1.4	1.3	1.2	1.1	1.1	1.0	0.9	0.8
$L_{MP,omf}$	11.2	1.4	1.5	1.6	1.6	1.7	1.7	1.7	1.8	1.6	1.5	1.4	1.3	1.2	1.1	1.1	1.0	0.9	0.8
$L_{MP,lf}$	370.2	46.0	50.7	54.8	58.3	61.3	64.2	67.0	70.0	65.7	62.2	59.3	57.1	55.2	53.6	52.0	50.4	48.6	46.3
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	232.9	28.2	30.2	31.7	32.7	33.4	33.9	34.3	34.6	31.3	28.6	26.3	24.3	22.5	21.0	19.5	18.0	16.5	15.0
$Stock_{Use}$	6501.4	6547.0	6598.9	6656.3	6718.9	6786.2	6857.8	6933.3	7012.5	7085.5	7151.9	7210.9	7261.7	7302.7	7332.0	7347.2	7345.6	7323.8	7278.1
$\sum R$	113.6	128.5	146.0	165.9	188.3	213.3	241.2	272.4	307.5	343.8	382.2	424.0	470.4	522.9	582.9	652.3	732.8	826.4	934.9
$\sum L_{OMF}$	244.1	273.7	305.5	339.0	373.7	409.5	446.2	484.0	522.9	559.7	595.0	629.9	665.2	701.6	739.9	780.8	825.1	873.3	926.0
$\sum L_{LF}$	396.1	445.2	499.4	557.7	619.6	684.8	752.8	823.9	898.0	967.7	1033.6	1096.7	1157.5	1216.6	1274.3	1330.8	1386.0	1439.8	1491.9
$\sum L_{Env}$	11.2	12.6	14.1	15.6	17.3	18.9	20.7	22.4	24.2	25.8	27.3	28.7	30.0	31.2	32.4	33.4	34.4	35.3	36.2

Table A 6: Results – CIGS PV Cells – Indium – Material production alternative (Scenario A) – Max

Material production alternative (Scenario A) - Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1925.6	4344.5	6445.6	8379.2	10161.9	11812.0	13350.2	14800.2	16188.1	17234.0	18291.5	19387.9	20549.9	21801.4	23161.6	24642.1	26243.5	27952.7	29740.5
$L_{F\&M,LF}$	44.4	96.6	138.2	172.9	201.6	225.1	244.2	259.4	271.5	276.3	279.9	282.7	285.0	287.2	289.3	291.2	292.8	293.8	293.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.4	0.9	1.6	2.9	4.8	7.6	11.6	17.1	24.5	34.3	46.9	62.7	82.4	106.4	135.1	168.8	207.7
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.8	1.3	1.9	2.7	3.8	5.2	7.0	9.2	11.8	15.0	18.8	23.1
$R_{F\&M}$	194.9	460.0	711.7	962.1	1209.9	1454.7	1696.7	1936.9	2177.1	2377.3	2583.3	2798.6	3026.8	3271.5	3535.5	3820.8	4127.3	4452.9	4792.4
$R_{F\&M,EOL}$	0.1	0.3	0.6	1.3	2.5	4.4	7.5	12.2	19.0	28.8	42.5	61.1	86.0	118.7	160.7	213.9	280.0	360.8	458.1
$Out_{MP} = In_{FM}$	1251.6	2839.6	4236.2	5537.3	6752.0	7891.1	8966.9	9994.2	10989.9	11762.2	12550.0	13372.3	14247.9	15194.3	16226.0	17352.1	18574.5	19885.2	21264.5
$Out_{FM} = In_{Use}$	612.7	1413.2	2142.8	2846.2	3525.7	4184.9	4828.7	5463.5	6097.6	6622.1	7168.1	7747.0	8370.6	9050.8	9797.8	10619.5	11519.3	12494.6	13534.8
$Out_{Use} = In_{EOL}$	0.2	0.5	1.1	2.3	4.3	7.6	12.8	20.6	31.9	47.8	69.8	99.2	138.1	188.4	252.3	332.1	430.1	548.4	688.8
$L_{MP,env}$	19.3	42.2	60.9	76.8	90.3	101.7	111.3	119.2	125.9	129.3	132.1	134.6	137.0	139.3	141.5	143.7	145.8	147.5	148.7
$L_{MP,omf}$	19.3	42.2	60.9	76.8	90.3	101.7	111.3	119.2	125.9	129.3	132.1	134.6	137.0	139.3	141.5	143.7	145.8	147.5	148.7
$L_{MP,lf}$	635.4	1420.4	2087.6	2688.3	3229.2	3717.5	4160.8	4567.5	4946.4	5213.3	5477.3	5746.4	6028.0	6328.4	6652.5	7002.5	7377.3	7772.4	8178.6
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	399.7	869.8	1243.5	1556.1	1814.8	2026.3	2197.4	2334.4	2443.7	2486.5	2518.7	2544.0	2565.4	2584.9	2603.4	2620.7	2635.1	2644.0	2643.5
$Stock_{Use}$	10742.5	12155.1	14296.8	17140.7	20662.1	24839.3	29655.2	35098.1	41163.8	47738.1	54836.5	62484.3	70716.8	79579.1	89124.6	99412.0	110501.2	122447.4	135293.4
$\sum R$	195.0	655.3	1367.7	2331.1	3543.5	5002.6	6706.7	8655.8	10851.8	13257.9	15883.7	18743.4	21856.2	25246.4	28942.6	32977.3	37384.6	42198.3	47448.7
$\sum L_{OMF}$	419.0	1331.2	2636.0	4269.8	6176.6	8307.5	10620.9	13082.2	15663.5	18296.4	20971.7	23684.7	26434.0	29220.9	32048.3	34919.1	37835.2	40795.5	43795.4
$\sum L_{LF}$	679.9	2196.9	4422.8	7284.1	10715.2	14658.2	19063.7	23891.4	29110.5	34602.0	40361.9	46394.7	52712.9	59335.6	66286.5	73592.0	81277.1	89362.1	97857.5
$\sum L_{Env}$	19.3	61.5	122.4	199.2	289.5	391.2	502.5	621.7	747.6	876.9	1009.0	1143.6	1280.6	1419.9	1561.4	1705.2	1851.0	1998.5	2147.2

Table A 7: Results – CIGS PV Cells – Indium – Material production alternative (Scenario C) – Min

Material production alternative (Scenario C) - Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	2604.5	328.5	367.8	403.0	435.0	465.0	494.1	523.9	555.7	529.5	508.9	493.2	481.6	473.2	466.6	460.5	453.5	443.9	430.2
$L_{F\&M,LF}$	25.9	3.1	3.4	3.5	3.6	3.7	3.8	3.8	3.8	3.5	3.2	2.9	2.7	2.5	2.3	2.2	2.0	1.8	1.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.1	0.2	0.4	0.7	1.1	1.7	2.6	3.8	5.3	7.2	9.7	12.6	16.2	20.4	25.2	30.8	36.9
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.4	0.6	0.8	1.1	1.4	1.8	2.3	2.8	3.4	4.1
$R_{F\&M}$	113.5	14.9	17.3	19.6	21.8	24.0	26.2	28.4	30.8	30.0	29.3	28.9	28.6	28.5	28.5	28.4	28.2	27.8	27.2
$R_{F\&M,EOL}$	0.0	0.1	0.2	0.3	0.6	1.0	1.7	2.8	4.2	6.3	9.1	12.9	17.7	23.9	31.6	41.0	52.3	65.7	81.4
$Out_{MP} = In_{FM}$	729.2	92.0	103.0	112.8	121.8	130.2	138.4	146.7	155.6	148.3	142.5	138.1	134.9	132.5	130.7	129.0	127.0	124.3	120.5
$Out_{FM} = In_{Use}$	357.0	45.8	52.1	58.0	63.6	69.0	74.5	80.2	86.3	83.5	81.4	80.0	79.2	78.9	78.9	78.9	78.7	78.1	76.7
$Out_{Use} = In_{EOL}$	0.1	0.1	0.3	0.5	1.0	1.8	2.9	4.7	7.1	10.5	15.0	20.9	28.5	37.9	49.6	63.7	80.4	99.9	122.3
$L_{MP,env}$	26.0	3.3	3.7	4.0	4.4	4.6	4.9	5.2	5.6	5.3	5.1	4.9	4.8	4.7	4.7	4.6	4.5	4.4	4.3
$L_{MP,omf}$	26.0	3.3	3.7	4.0	4.4	4.6	4.9	5.2	5.6	5.3	5.1	4.9	4.8	4.7	4.7	4.6	4.5	4.4	4.3
$L_{MP,lf}$	1823.1	229.9	257.4	282.1	304.5	325.5	345.9	366.7	389.0	370.7	356.2	345.2	337.2	331.2	326.6	322.4	317.4	310.7	301.2
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	232.9	28.2	30.2	31.7	32.7	33.4	33.9	34.3	34.6	31.3	28.6	26.3	24.3	22.5	21.0	19.5	18.0	16.5	15.0
$Stock_{Use}$	6501.4	6547.0	6598.9	6656.3	6718.9	6786.2	6857.8	6933.3	7012.5	7085.5	7151.9	7210.9	7261.7	7302.7	7332.0	7347.2	7345.6	7323.8	7278.1
$\sum R$	113.6	128.5	146.0	165.9	188.3	213.3	241.2	272.4	307.5	343.8	382.2	424.0	470.4	522.9	582.9	652.3	732.8	826.4	934.9
$\sum L_{OMF}$	258.9	290.4	324.4	360.4	397.9	436.6	476.5	517.8	560.5	600.9	639.9	678.3	717.1	757.0	798.8	843.3	891.1	942.8	999.0
$\sum L_{LF}$	1849.0	2082.1	2342.9	2628.5	2936.7	3266.0	3615.8	3986.5	4379.6	4754.2	5114.1	5463.1	5804.0	6139.2	6469.9	6796.7	7119.0	7434.9	7741.8
$\sum L_{Env}$	26.0	29.3	33.0	37.0	41.4	46.0	51.0	56.2	61.8	67.1	72.2	77.1	81.9	86.6	91.3	95.9	100.4	104.9	109.2

Table A 8: Results – CIGS PV Cells – Indium – Material production alternative (Scenario C) – Max

Material production alternative (Scenario C) - Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	4470.1	10141.5	15129.2	19776.0	24114.4	28182.3	32024.6	35693.6	39249.7	42007.8	44821.5	47758.2	50885.4	54265.5	57950.0	61971.9	66337.6	71018.7	75944.6
$L_{F\&M,LF}$	44.4	96.6	138.2	172.9	201.6	225.1	244.2	259.4	271.5	276.3	279.9	282.7	285.0	287.2	289.3	291.2	292.8	293.8	293.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.4	0.9	1.6	2.9	4.8	7.6	11.6	17.1	24.5	34.3	46.9	62.7	82.4	106.4	135.1	168.8	207.7
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.8	1.3	1.9	2.7	3.8	5.2	7.0	9.2	11.8	15.0	18.8	23.1
$R_{F\&M}$	194.9	460.0	711.7	962.1	1209.9	1454.7	1696.7	1936.9	2177.1	2377.3	2583.3	2798.6	3026.8	3271.5	3535.5	3820.8	4127.3	4452.9	4792.4
$R_{F\&M,EOL}$	0.1	0.3	0.6	1.3	2.5	4.4	7.5	12.2	19.0	28.8	42.5	61.1	86.0	118.7	160.7	213.9	280.0	360.8	458.1
$Out_{MP} = In_{FM}$	1251.6	2839.6	4236.2	5537.3	6752.0	7891.1	8966.9	9994.2	10989.9	11762.2	12550.0	13372.3	14247.9	15194.3	16226.0	17352.1	18574.5	19885.2	21264.5
$Out_{FM} = In_{Use}$	612.7	1413.2	2142.8	2846.2	3525.7	4184.9	4828.7	5463.5	6097.6	6622.1	7168.1	7747.0	8370.6	9050.8	9797.8	10619.5	11519.3	12494.6	13534.8
$Out_{Use} = In_{EOL}$	0.2	0.5	1.1	2.3	4.3	7.6	12.8	20.6	31.9	47.8	69.8	99.2	138.1	188.4	252.3	332.1	430.1	548.4	688.8
$L_{MP,env}$	44.7	101.4	151.3	197.8	241.1	281.8	320.2	356.9	392.5	420.1	448.2	477.6	508.9	542.7	579.5	619.7	663.4	710.2	759.4
$L_{MP,omf}$	44.7	101.4	151.3	197.8	241.1	281.8	320.2	356.9	392.5	420.1	448.2	477.6	508.9	542.7	579.5	619.7	663.4	710.2	759.4
$L_{MP,lf}$	3129.1	7099.1	10590.4	13843.2	16880.1	19727.6	22417.2	24985.5	27474.8	29405.5	31375.0	33430.7	35619.7	37985.8	40565.0	43380.3	46436.3	49713.1	53161.2
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	399.7	869.8	1243.5	1556.1	1814.8	2026.3	2197.4	2334.4	2443.7	2486.5	2518.7	2544.0	2565.4	2584.9	2603.4	2620.7	2635.1	2644.0	2643.5
$Stock_{Use}$	10742.5	12155.1	14296.8	17140.7	20662.1	24839.3	29655.2	35098.1	41163.8	47738.1	54836.5	62484.3	70716.8	79579.1	89124.6	99412.0	110501.2	122447.4	135293.4
$\sum R$	195.0	655.3	1367.7	2331.1	3543.5	5002.6	6706.7	8655.8	10851.8	13257.9	15883.7	18743.4	21856.2	25246.4	28942.6	32977.3	37384.6	42198.3	47448.7
$\sum L_{OMF}$	444.5	1415.9	2811.1	4565.8	6623.4	8934.5	11456.9	14155.8	17003.7	19927.4	22918.9	25974.8	29095.9	32286.2	35551.6	38898.4	42332.0	45855.0	49465.6
$\sum L_{LF}$	3173.5	10369.2	21097.9	35114.1	52195.9	72149.0	94811.0	120056.7	147804.3	177488.0	209145.6	242862.8	278772.8	317052.8	357916.2	401599.6	448343.7	498369.3	551847.3
$\sum L_{Env}$	44.7	146.1	297.4	495.2	736.3	1018.1	1338.4	1695.3	2087.8	2507.9	2956.1	3433.7	3942.5	4485.2	5064.7	5684.4	6347.8	7058.0	7817.4

Table A 9: Results – CIGS PV Cells – Indium – F&M-I scenarios – Low Efficiency – Min

F&M-I scenarios - Low Efficiency - Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	2704.3	340.3	380.2	415.6	447.5	477.2	505.8	534.9	565.9	537.8	515.5	498.2	485.2	475.4	467.4	460.0	451.6	440.8	426.0
$L_{F\&M,LF}$	78.6	9.6	10.5	11.2	11.8	12.2	12.6	12.9	13.3	12.2	11.3	10.6	10.0	9.4	8.9	8.4	8.0	7.4	6.9
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.1	0.2	0.4	0.7	1.1	1.7	2.6	3.8	5.3	7.2	9.7	12.6	16.2	20.4	25.2	30.8	36.9
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.4	0.6	0.8	1.1	1.4	1.8	2.3	2.8	3.4	4.1
$R_{F\&M}$	344.8	45.9	54.2	62.3	70.5	78.8	87.3	96.4	106.2	105.0	104.6	104.9	105.8	107.3	109.0	110.8	112.2	112.8	112.3
$R_{F\&M,EOL}$	0.0	0.1	0.2	0.3	0.6	1.0	1.7	2.8	4.2	6.3	9.1	12.9	17.7	23.9	31.6	41.0	52.3	65.7	81.4
$Out_{MP} = In_{FM}$	1487.4	188.2	211.4	232.4	251.6	269.7	287.5	305.6	325.1	310.6	299.3	290.8	284.7	280.3	277.1	274.1	270.5	265.3	257.7
$Out_{FM} = In_{Use}$	357.0	45.8	52.1	58.0	63.6	69.0	74.5	80.2	86.3	83.5	81.4	80.0	79.2	78.9	78.9	78.9	78.7	78.1	76.7
$Out_{Use} = In_{EOL}$	0.1	0.1	0.3	0.5	1.0	1.8	2.9	4.7	7.1	10.5	15.0	20.9	28.5	37.9	49.6	63.7	80.4	99.9	122.3
$L_{MP,env}$	27.0	3.3	3.6	3.8	4.0	4.1	4.2	4.3	4.4	4.0	3.7	3.5	3.2	3.0	2.9	2.7	2.5	2.3	2.1
$L_{MP,omf}$	27.0	3.3	3.6	3.8	4.0	4.1	4.2	4.3	4.4	4.0	3.7	3.5	3.2	3.0	2.9	2.7	2.5	2.3	2.1
$L_{MP,lf}$	1162.8	145.5	161.6	175.6	188.0	199.2	209.9	220.6	232.0	219.2	208.8	200.5	194.1	189.0	184.6	180.6	176.1	170.8	164.0
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	707.1	86.8	94.6	100.8	105.8	109.7	113.1	116.2	119.3	109.9	102.0	95.3	89.7	84.7	80.3	76.0	71.6	67.0	61.9
$Stock_{Use}$	6501.4	6547.0	6598.9	6656.3	6718.9	6786.2	6857.8	6933.3	7012.5	7085.5	7151.9	7210.9	7261.7	7302.7	7332.0	7347.2	7345.6	7323.8	7278.1
$\sum R$	344.8	390.8	445.1	507.8	578.9	658.7	747.7	846.8	957.3	1068.7	1182.4	1300.2	1423.7	1554.9	1695.4	1847.2	2011.7	2190.2	2383.9
$\sum L_{OMF}$	734.1	824.3	922.7	1027.5	1137.6	1252.1	1370.5	1492.7	1619.0	1736.6	1847.6	1953.6	2056.2	2156.6	2255.9	2355.0	2454.4	2554.4	2655.4
$\sum L_{LF}$	1241.4	1396.5	1568.6	1755.4	1955.2	2166.7	2389.3	2623.1	2868.6	3100.4	3321.1	3533.0	3738.2	3937.9	4133.3	4324.6	4511.5	4693.1	4868.1
$\sum L_{Env}$	27.0	30.4	33.9	37.8	41.7	45.8	50.1	54.4	58.8	62.8	66.5	70.0	73.2	76.3	79.1	81.8	84.3	86.6	88.8

Table A 10: Results – CIGS PV Cells – Indium – F&M-I scenarios – Low Efficiency – Max

F&M-I scenarios - Low Efficiency - Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	4641.5	10507.0	15638.6	20394.0	24808.2	28922.0	32782.8	36445.2	39971.7	42667.4	45402.8	48245.7	51262.8	54515.0	58051.7	61903.1	66072.6	70528.7	75198.8
$L_{F\&M,LF}$	134.8	297.9	432.6	549.8	651.4	739.0	814.4	879.4	936.0	968.5	997.9	1025.6	1052.6	1079.8	1107.6	1135.9	1164.1	1190.9	1214.5
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.4	0.9	1.6	2.9	4.8	7.6	11.6	17.1	24.5	34.3	46.9	62.7	82.4	106.4	135.1	168.8	207.7
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.8	1.3	1.9	2.7	3.8	5.2	7.0	9.2	11.8	15.0	18.8	23.1
$R_{F\&M}$	591.7	1418.3	2228.4	3059.3	3908.3	4774.4	5659.2	6566.8	7504.5	8333.5	9211.5	10153.8	11177.3	12299.7	13537.7	14905.1	16409.7	18050.8	19815.5
R_{EOL}	0.1	0.3	0.6	1.3	2.5	4.4	7.5	12.2	19.0	28.8	42.5	61.1	86.0	118.7	160.7	213.9	280.0	360.8	458.1
$Out_{MP} = In_{FM}$	2552.8	5810.9	8696.8	11403.6	13947.7	16349.0	18631.5	20824.4	22961.5	24640.4	26358.9	28156.7	30074.2	32148.7	34411.8	36884.0	39570.1	42454.3	45495.3
$Out_{FM} = In_{Use}$	612.7	1413.2	2142.8	2846.2	3525.7	4184.9	4828.7	5463.5	6097.6	6622.1	7168.1	7747.0	8370.6	9050.8	9797.8	10619.5	11519.3	12494.6	13534.8
$Out_{Use} = In_{EOL}$	0.2	0.5	1.1	2.3	4.3	7.6	12.8	20.6	31.9	47.8	69.8	99.2	138.1	188.4	252.3	332.1	430.1	548.4	688.8
$L_{MP,env}$	46.4	102.2	147.7	186.9	220.5	249.1	273.2	293.6	310.9	320.0	327.9	335.0	341.8	348.3	354.8	361.1	367.1	372.2	376.0
$L_{MP,omf}$	46.4	102.2	147.7	186.9	220.5	249.1	273.2	293.6	310.9	320.0	327.9	335.0	341.8	348.3	354.8	361.1	367.1	372.2	376.0
$L_{MP,lf}$	1995.8	4491.7	6646.4	8616.5	10419.5	12075.0	13604.8	15033.6	16388.4	17387.0	18388.1	19418.9	20505.1	21669.7	22930.4	24297.0	25768.3	27329.9	28951.5
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	1213.6	2681.5	3893.1	4948.4	5862.4	6650.7	7329.3	7914.7	8423.6	8716.4	8981.3	9230.3	9473.6	9718.5	9968.7	10223.4	10477.0	10718.1	10930.5
$Stock_{Use}$	10742.5	12155.1	14296.8	17140.7	20662.1	24839.3	29655.2	35098.1	41163.8	47738.1	54836.5	62484.3	70716.8	79579.1	89124.6	99412.0	110501.2	122447.4	135293.4
$\sum R$	591.9	2010.4	4239.5	7300.1	11210.8	15989.7	21656.3	28235.3	35758.7	44121.0	53375.0	63590.0	74853.3	87271.7	100970.1	116089.0	132778.8	151190.4	171463.9
$\sum L_{OMF}$	1260.1	4043.9	8085.2	13221.4	19305.9	26208.6	33815.8	42031.7	50777.8	59831.3	69165.0	78764.6	88626.8	98756.3	109162.2	119853.1	130832.3	142091.4	153605.5
$\sum L_{LF}$	2130.7	6920.4	13999.4	23165.8	34236.8	47051.1	61470.8	77384.7	94710.3	113067.7	132456.5	152904.8	174467.7	197224.2	221271.5	246716.2	273663.6	302203.2	332392.3
$\sum L_{Env}$	46.4	148.6	296.3	483.2	703.7	952.8	1226.0	1519.6	1830.4	2150.5	2478.4	2813.4	3155.2	3503.4	3858.2	4219.3	4586.4	4958.6	5334.6

Table A 11: Results – CIGS PV Cells – Indium – F&M-I scenarios – High Efficiency – Min

F&M-I scenarios - High Efficiency - Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	827.8	104.8	117.7	129.4	140.1	150.1	159.9	170.0	180.7	172.6	166.2	161.4	157.9	155.4	153.5	151.7	149.6	146.6	142.2
$L_{F\&M,LF}$	6.8	0.8	0.9	0.9	0.9	1.0	1.0	1.0	1.0	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.1	0.2	0.4	0.7	1.1	1.7	2.6	3.8	5.3	7.2	9.7	12.6	16.2	20.4	25.2	30.8	36.9
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.4	0.6	0.8	1.1	1.4	1.8	2.3	2.8	3.4	4.1
$R_{F\&M}$	30.0	3.9	4.5	5.1	5.7	6.2	6.7	7.2	7.8	7.5	7.3	7.1	6.9	6.8	6.6	6.5	6.3	6.1	5.8
$R_{F\&M,EOL}$	0.0	0.1	0.2	0.3	0.6	1.0	1.7	2.8	4.2	6.3	9.1	12.9	17.7	23.9	31.6	41.0	52.3	65.7	81.4
$Out_{MP} = In_{FM}$	455.3	57.9	65.4	72.3	78.7	84.9	90.9	97.1	103.8	99.7	96.5	94.2	92.6	91.6	91.0	90.4	89.6	88.2	86.1
$Out_{FM} = In_{Use}$	357.0	45.8	52.1	58.0	63.6	69.0	74.5	80.2	86.3	83.5	81.4	80.0	79.2	78.9	78.9	78.9	78.7	78.1	76.7
$Out_{Use} = In_{EOL}$	0.1	0.1	0.3	0.5	1.0	1.8	2.9	4.7	7.1	10.5	15.0	20.9	28.5	37.9	49.6	63.7	80.4	99.9	122.3
$L_{MP,env}$	8.3	1.0	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.3	1.2	1.1	1.1	1.0	0.9	0.9	0.8	0.8	0.7
$L_{MP,omf}$	8.3	1.0	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.3	1.2	1.1	1.1	1.0	0.9	0.9	0.8	0.8	0.7
$L_{MP,lf}$	356.0	44.8	50.0	54.7	58.8	62.7	66.4	70.1	74.1	70.3	67.3	65.0	63.2	61.8	60.6	59.5	58.3	56.8	54.8
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	61.5	7.4	7.9	8.3	8.5	8.6	8.7	8.7	8.7	7.8	7.1	6.4	5.8	5.3	4.9	4.5	4.0	3.6	3.2
$Stock_{Use}$	6501.4	6547.0	6598.9	6656.3	6718.9	6786.2	6857.8	6933.3	7012.5	7085.5	7151.9	7210.9	7261.7	7302.7	7332.0	7347.2	7345.6	7323.8	7278.1
$\sum R$	30.0	34.0	38.7	44.2	50.4	57.6	66.1	76.1	88.1	101.9	118.3	138.2	162.9	193.6	231.8	279.3	337.9	409.8	497.0
$\sum L_{OMF}$	69.8	78.3	87.5	97.1	107.3	117.9	129.0	140.8	153.6	166.4	180.0	194.8	211.3	230.3	252.3	278.1	308.2	343.3	384.2
$\sum L_{LF}$	362.8	408.4	459.3	514.9	574.7	638.5	705.9	777.2	852.5	924.2	992.8	1059.3	1124.2	1188.0	1250.9	1313.2	1374.8	1435.4	1494.7
$\sum L_{Env}$	8.3	9.3	10.4	11.6	12.8	14.1	15.5	16.8	18.2	19.5	20.7	21.9	22.9	23.9	24.8	25.7	26.6	27.3	28.0

Table A 12: Results – CIGS PV Cells – Indium – F&M-I scenarios – High Efficiency – Max

F&M-I scenarios - High Efficiency - Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1420.9	3234.7	4841.4	6348.0	7763.2	9098.0	10365.4	11581.5	12764.9	13691.8	14638.8	15628.0	16681.4	17819.4	19059.3	20411.9	21879.4	23452.7	25108.5
$L_{F\&M,LF}$	11.7	25.5	36.3	45.2	52.4	58.2	62.7	66.1	68.6	69.1	69.2	69.0	68.7	68.2	67.5	66.7	65.7	64.5	62.9
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.4	0.9	1.6	2.9	4.8	7.6	11.6	17.1	24.5	34.3	46.9	62.7	82.4	106.4	135.1	168.8	207.7
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.8	1.3	1.9	2.7	3.8	5.2	7.0	9.2	11.8	15.0	18.8	23.1
$R_{F\&M}$	51.5	121.2	186.8	251.5	314.6	376.0	435.6	493.3	549.6	594.3	638.6	683.4	729.1	776.3	825.1	875.4	926.7	977.7	1026.6
$R_{F\&M,EOL}$	0.1	0.3	0.6	1.3	2.5	4.4	7.5	12.2	19.0	28.8	42.5	61.1	86.0	118.7	160.7	213.9	280.0	360.8	458.1
$Out_{MP} = In_{FM}$	781.5	1789.0	2692.3	3549.6	4364.7	5142.9	5891.0	6617.5	7332.7	7907.0	8498.7	9120.7	9786.4	10508.5	11297.9	12162.1	13103.4	14117.3	15190.6
$Out_{FM} = In_{Use}$	612.7	1413.2	2142.8	2846.2	3525.7	4184.9	4828.7	5463.5	6097.6	6622.1	7168.1	7747.0	8370.6	9050.8	9797.8	10619.5	11519.3	12494.6	13534.8
$Out_{Use} = In_{EOL}$	0.2	0.5	1.1	2.3	4.3	7.6	12.8	20.6	31.9	47.8	69.8	99.2	138.1	188.4	252.3	332.1	430.1	548.4	688.8
$L_{MP,env}$	14.2	31.4	45.7	58.2	69.0	78.3	86.4	93.3	99.3	102.7	105.7	108.5	111.2	113.8	116.5	119.1	121.6	123.8	125.5
$L_{MP,omf}$	14.2	31.4	45.7	58.2	69.0	78.3	86.4	93.3	99.3	102.7	105.7	108.5	111.2	113.8	116.5	119.1	121.6	123.8	125.5
$L_{MP,lf}$	611.0	1382.8	2057.6	2682.0	3260.6	3798.4	4301.7	4777.4	5233.6	5579.4	5928.7	6290.3	6672.6	7083.2	7528.4	8011.7	8533.0	9087.9	9666.8
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	105.6	229.1	326.4	406.7	471.9	523.8	564.1	594.6	617.0	621.6	622.7	621.2	618.0	613.4	607.5	600.4	591.6	580.5	566.3
$Stock_{Use}$	10742.5	12155.1	14296.8	17140.7	20662.1	24839.3	29655.2	35098.1	41163.8	47738.1	54836.5	62484.3	70716.8	79579.1	89124.6	99412.0	110501.2	122447.4	135293.4
$\sum R$	51.6	173.1	360.6	613.4	930.5	1310.9	1754.0	2259.5	2828.1	3451.1	4132.3	4876.8	5692.0	6586.9	7572.7	8662.0	9868.7	11207.2	12691.8
$\sum L_{OMF}$	119.9	380.7	753.3	1219.1	1761.6	2366.6	3021.9	3717.4	4445.2	5186.6	5939.6	6703.7	7479.7	8269.7	9076.1	9902.0	10750.3	11623.4	12522.9
$\sum L_{LF}$	622.7	2031.0	4124.9	6852.2	10165.4	14022.3	18387.2	23231.5	28534.9	34185.3	40185.9	46549.0	53295.5	60453.8	68058.9	76149.1	84762.8	93934.0	103686.8
$\sum L_{Env}$	14.2	45.7	91.4	149.6	218.6	296.9	383.3	476.6	575.9	678.6	784.3	892.8	1004.0	1117.9	1234.3	1353.4	1475.0	1598.7	1724.3

Table A 13: Results – CIGS PV Cells – Indium – F&M-II scenarios – Pessimistic – Min

F&M-II scenarios – Pessimistic - Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1325.9	166.3	185.2	201.8	216.7	230.3	243.4	256.7	270.9	256.7	245.4	236.6	229.9	224.7	220.4	216.4	212.0	206.5	199.1
$L_{F\&M,LF}$	26.3	3.2	3.5	3.7	3.8	4.0	4.0	4.1	4.2	3.9	3.6	3.3	3.1	2.9	2.8	2.6	2.5	2.3	2.1
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.1	0.2	0.4	0.7	1.1	1.7	2.6	3.8	5.3	7.2	9.7	12.6	16.2	20.4	25.2	30.8	36.9
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.4	0.6	0.8	1.1	1.4	1.8	2.3	2.8	3.4	4.1
$R_{F\&M}$	109.5	14.1	16.2	18.1	19.9	21.6	23.4	25.1	27.0	26.0	25.3	24.7	24.4	24.1	23.9	23.7	23.4	23.0	22.3
$R_{F\&M,EOL}$	0.0	0.1	0.2	0.3	0.6	1.0	1.7	2.8	4.2	6.3	9.1	12.9	17.7	23.9	31.6	41.0	52.3	65.7	81.4
$Out_{MP} = In_{FM}$	729.2	92.0	103.0	112.8	121.8	130.2	138.4	146.7	155.6	148.3	142.5	138.1	134.9	132.5	130.7	129.0	127.0	124.3	120.5
$Out_{FM} = In_{Use}$	357.0	45.8	52.1	58.0	63.6	69.0	74.5	80.2	86.3	83.5	81.4	80.0	79.2	78.9	78.9	78.9	78.7	78.1	76.7
$Out_{Use} = In_{EOL}$	0.1	0.1	0.3	0.5	1.0	1.8	2.9	4.7	7.1	10.5	15.0	20.9	28.5	37.9	49.6	63.7	80.4	99.9	122.3
$L_{MP,env}$	13.3	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0
$L_{MP,omf}$	13.3	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0
$L_{MP,lf}$	570.1	71.1	78.7	85.3	91.0	96.2	101.0	105.9	111.1	104.6	99.4	95.2	92.0	89.3	87.1	84.9	82.7	80.0	76.7
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	236.5	28.9	31.2	33.1	34.5	35.6	36.4	37.2	38.0	34.9	32.2	30.0	28.1	26.5	25.1	23.7	22.3	20.9	19.3
$Stock_{Use}$	6501.4	6547.0	6598.9	6656.3	6718.9	6786.2	6857.8	6933.3	7012.5	7085.5	7151.9	7210.9	7261.7	7302.7	7332.0	7347.2	7345.6	7323.8	7278.1
$\sum R$	109.5	123.7	140.0	158.4	178.9	201.6	226.7	254.6	285.8	318.2	352.6	390.3	432.4	480.4	535.9	600.6	676.3	765.1	868.8
$\sum L_{OMF}$	249.8	280.4	313.4	348.6	385.3	423.5	463.1	504.1	546.8	587.4	626.7	665.6	704.9	745.5	788.1	833.4	882.2	934.9	992.1
$\sum L_{LF}$	596.4	670.7	752.9	841.9	936.7	1036.9	1142.1	1252.3	1367.9	1476.8	1580.4	1679.8	1775.9	1869.6	1961.2	2051.1	2139.0	2224.8	2307.7
$\sum L_{Env}$	13.3	14.9	16.6	18.5	20.4	22.4	24.4	26.5	28.6	30.5	32.3	33.9	35.5	36.9	38.2	39.5	40.7	41.8	42.8

Table A 14: Results – CIGS PV Cells – Indium – F&M-II scenarios – Pessimistic – Max

F&M-II scenarios – Pessimistic – Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	2275.7	5134.4	7617.5	9902.7	12009.5	13959.6	15777.5	17491.1	19131.4	20367.4	21617.2	22913.0	24286.2	25765.2	27372.8	29122.5	31015.0	33035.0	35147.9
$L_{F\&M,LF}$	45.1	99.0	142.8	180.3	212.3	239.4	262.4	281.8	298.4	307.4	315.4	322.9	330.3	337.9	345.8	354.1	362.6	371.0	378.8
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.4	0.9	1.6	2.9	4.8	7.6	11.6	17.1	24.5	34.3	46.9	62.7	82.4	106.4	135.1	168.8	207.7
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.8	1.3	1.9	2.7	3.8	5.2	7.0	9.2	11.8	15.0	18.8	23.1
$R_{F\&M}$	187.9	436.5	665.7	888.1	1103.4	1312.0	1514.6	1712.6	1908.0	2066.3	2228.1	2396.4	2574.2	2764.6	2969.8	3191.3	3428.8	3680.6	3942.1
$R_{F\&M,EOL}$	0.1	0.3	0.6	1.3	2.5	4.4	7.5	12.2	19.0	28.8	42.5	61.1	86.0	118.7	160.7	213.9	280.0	360.8	458.1
$Out_{MP} = In_{FM}$	1251.6	2839.6	4236.2	5537.3	6752.0	7891.1	8966.9	9994.2	10989.9	11762.2	12550.0	13372.3	14247.9	15194.3	16226.0	17352.1	18574.5	19885.2	21264.5
$Out_{FM} = In_{Use}$	612.7	1413.2	2142.8	2846.2	3525.7	4184.9	4828.7	5463.5	6097.6	6622.1	7168.1	7747.0	8370.6	9050.8	9797.8	10619.5	11519.3	12494.6	13534.8
$Out_{Use} = In_{EOL}$	0.2	0.5	1.1	2.3	4.3	7.6	12.8	20.6	31.9	47.8	69.8	99.2	138.1	188.4	252.3	332.1	430.1	548.4	688.8
$L_{MP,env}$	22.8	49.9	71.9	90.8	106.8	120.2	131.5	140.9	148.8	152.8	156.1	159.1	161.9	164.6	167.3	169.9	172.3	174.4	175.7
$L_{MP,omf}$	22.8	49.9	71.9	90.8	106.8	120.2	131.5	140.9	148.8	152.8	156.1	159.1	161.9	164.6	167.3	169.9	172.3	174.4	175.7
$L_{MP,lf}$	978.5	2195.0	3237.4	4183.9	5044.0	5828.1	6547.7	7215.1	7843.9	8299.7	8755.0	9222.5	9714.5	10241.7	10812.3	11430.6	12095.8	12801.1	13531.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	406.0	891.0	1284.9	1622.7	1910.6	2154.8	2361.3	2536.3	2685.9	2766.4	2838.4	2906.0	2972.7	3041.1	3112.5	3187.2	3263.7	3339.1	3408.8
$Stock_{Use}$	10742.5	12155.1	14296.8	17140.7	20662.1	24839.3	29655.2	35098.1	41163.8	47738.1	54836.5	62484.3	70716.8	79579.1	89124.6	99412.0	110501.2	122447.4	135293.4
$\sum R$	188.0	624.8	1291.1	2180.5	3286.4	4602.8	6124.9	7849.6	9776.6	11871.7	14142.3	16599.8	19260.1	22143.4	25274.0	28679.1	32387.9	36429.3	40829.5
$\sum L_{OMF}$	428.8	1369.9	2727.2	4441.6	6460.6	8738.5	11236.0	13920.8	16767.1	19703.4	22722.4	25821.9	29003.3	32271.8	35634.0	39097.5	42668.7	46350.9	50143.1
$\sum L_{LF}$	1023.7	3317.7	6697.9	11062.2	16318.7	22386.6	29197.1	36694.9	44838.4	53447.4	62520.5	72069.7	82119.7	92706.3	103873.5	115670.0	128143.5	141334.4	155268.1
$\sum L_{Env}$	22.8	72.7	144.6	235.4	342.1	462.4	593.8	734.7	883.5	1036.3	1192.4	1351.5	1513.4	1678.0	1845.3	2015.2	2187.5	2361.9	2537.6

Table A 15: Results – CIGS PV Cells – Indium – F&M-II scenarios – Optimistic – Min

F&M-II scenarios – Optimistic – Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1325.9	166.3	185.2	201.8	216.7	230.3	243.4	256.7	270.9	256.7	245.4	236.6	229.9	224.7	220.4	216.4	212.0	206.5	199.1
$L_{F\&M,LF}$	25.0	3.0	3.2	3.3	3.4	3.4	3.4	3.4	3.3	3.0	2.6	2.4	2.1	1.9	1.7	1.6	1.4	1.2	1.1
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.1	0.2	0.4	0.7	1.1	1.7	2.6	3.8	5.3	7.2	9.7	12.6	16.2	20.4	25.2	30.8	36.9
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.4	0.6	0.8	1.1	1.4	1.8	2.3	2.8	3.4	4.1
$R_{F\&M}$	122.1	16.3	19.1	21.9	24.7	27.4	30.1	33.0	36.0	35.2	34.7	34.4	34.3	34.3	34.4	34.4	34.3	34.0	33.3
$R_{F\&M,EOL}$	0.0	0.1	0.2	0.3	0.6	1.0	1.7	2.8	4.2	6.3	9.1	12.9	17.7	23.9	31.6	41.0	52.3	65.7	81.4
$Out_{MP} = In_{FM}$	729.2	92.0	103.0	112.8	121.8	130.2	138.4	146.7	155.6	148.3	142.5	138.1	134.9	132.5	130.7	129.0	127.0	124.3	120.5
$Out_{FM} = In_{Use}$	357.0	45.8	52.1	58.0	63.6	69.0	74.5	80.2	86.3	83.5	81.4	80.0	79.2	78.9	78.9	78.9	78.7	78.1	76.7
$Out_{Use} = In_{EOL}$	0.1	0.1	0.3	0.5	1.0	1.8	2.9	4.7	7.1	10.5	15.0	20.9	28.5	37.9	49.6	63.7	80.4	99.9	122.3
$L_{MP,env}$	13.3	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0
$L_{MP,omf}$	13.3	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0
$L_{MP,lf}$	570.1	71.1	78.7	85.3	91.0	96.2	101.0	105.9	111.1	104.6	99.4	95.2	92.0	89.3	87.1	84.9	82.7	80.0	76.7
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	225.2	26.9	28.6	29.6	30.2	30.4	30.3	30.2	29.9	26.6	23.8	21.3	19.2	17.4	15.7	14.0	12.5	11.0	9.5
$Stock_{Use}$	6501.4	6547.0	6598.9	6656.3	6718.9	6786.2	6857.8	6933.3	7012.5	7085.5	7151.9	7210.9	7261.7	7302.7	7332.0	7347.2	7345.6	7323.8	7278.1
$\sum R$	122.1	138.5	157.8	180.0	205.3	233.7	265.5	301.3	341.5	383.1	426.9	474.2	526.2	584.4	650.4	725.8	812.5	912.2	1026.8
$\sum L_{OMF}$	238.4	267.0	297.5	329.1	361.6	394.7	428.1	462.1	496.7	529.0	559.8	590.0	620.4	651.8	685.0	720.7	759.7	802.5	849.8
$\sum L_{LF}$	595.2	669.2	751.1	839.7	934.1	1033.7	1138.2	1247.7	1362.3	1470.3	1572.9	1671.4	1766.5	1859.2	1949.8	2038.5	2125.4	2210.1	2291.9
$\sum L_{Env}$	13.3	14.9	16.6	18.5	20.4	22.4	24.4	26.5	28.6	30.5	32.3	33.9	35.5	36.9	38.2	39.5	40.7	41.8	42.8

Table A 16: Results – CIGS PV Cells – Indium – F&M-II scenarios – Optimistic – Max

F&M-II scenarios – Optimistic – Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	2275.7	5134.4	7617.5	9902.7	12009.5	13959.6	15777.5	17491.1	19131.4	20367.4	21617.2	22913.0	24286.2	25765.2	27372.8	29122.5	31015.0	33035.0	35147.9
$L_{F\&M,LF}$	42.9	92.4	130.6	161.5	185.8	204.6	218.5	228.3	234.8	234.4	232.5	229.5	225.7	221.2	216.0	210.1	203.2	195.1	185.5
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.4	0.9	1.6	2.9	4.8	7.6	11.6	17.1	24.5	34.3	46.9	62.7	82.4	106.4	135.1	168.8	207.7
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.8	1.3	1.9	2.7	3.8	5.2	7.0	9.2	11.8	15.0	18.8	23.1
$R_{F\&M}$	209.6	502.1	787.1	1076.4	1368.0	1660.4	1953.2	2247.2	2544.0	2796.2	3056.9	3330.2	3620.4	3931.9	4268.3	4632.0	5023.3	5439.5	5874.5
$R_{F\&M,EOL}$	0.1	0.3	0.6	1.3	2.5	4.4	7.5	12.2	19.0	28.8	42.5	61.1	86.0	118.7	160.7	213.9	280.0	360.8	458.1
$Out_{MP} = In_{FM}$	1251.6	2839.6	4236.2	5537.3	6752.0	7891.1	8966.9	9994.2	10989.9	11762.2	12550.0	13372.3	14247.9	15194.3	16226.0	17352.1	18574.5	19885.2	21264.5
$Out_{FM} = In_{Use}$	612.7	1413.2	2142.8	2846.2	3525.7	4184.9	4828.7	5463.5	6097.6	6622.1	7168.1	7747.0	8370.6	9050.8	9797.8	10619.5	11519.3	12494.6	13534.8
$Out_{Use} = In_{EOL}$	0.2	0.5	1.1	2.3	4.3	7.6	12.8	20.6	31.9	47.8	69.8	99.2	138.1	188.4	252.3	332.1	430.1	548.4	688.8
$L_{MP,env}$	22.8	49.9	71.9	90.8	106.8	120.2	131.5	140.9	148.8	152.8	156.1	159.1	161.9	164.6	167.3	169.9	172.3	174.4	175.7
$L_{MP,omf}$	22.8	49.9	71.9	90.8	106.8	120.2	131.5	140.9	148.8	152.8	156.1	159.1	161.9	164.6	167.3	169.9	172.3	174.4	175.7
$L_{MP,lf}$	978.5	2195.0	3237.4	4183.9	5044.0	5828.1	6547.7	7215.1	7843.9	8299.7	8755.0	9222.5	9714.5	10241.7	10812.3	11430.6	12095.8	12801.1	13531.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	386.4	831.9	1175.6	1453.2	1672.5	1841.2	1966.5	2055.1	2113.5	2109.5	2092.5	2065.6	2031.2	1990.5	1943.9	1890.5	1828.7	1756.0	1669.6
$Stock_{Use}$	10742.5	12155.1	14296.8	17140.7	20662.1	24839.3	29655.2	35098.1	41163.8	47738.1	54836.5	62484.3	70716.8	79579.1	89124.6	99412.0	110501.2	122447.4	135293.4
$\sum R$	209.7	712.1	1499.9	2577.6	3948.1	5612.9	7573.6	9833.0	12396.0	15221.0	18320.4	21711.7	25418.1	29468.7	33897.7	38743.7	44047.0	49847.3	56179.9
$\sum L_{OMF}$	409.3	1291.3	2539.3	4084.2	5865.1	7829.4	9932.1	12135.7	14409.7	16689.0	18962.2	21221.2	23461.1	25679.0	27872.6	30039.4	32175.5	34274.7	36327.7
$\sum L_{LF}$	1021.5	3308.9	6677.0	11022.5	16252.5	22285.6	29052.3	36496.5	44576.5	53112.5	62102.7	71558.5	81503.9	91973.7	103011.1	114663.6	126977.6	139992.6	153733.1
$\sum L_{Env}$	22.8	72.7	144.6	235.4	342.1	462.4	593.8	734.7	883.5	1036.3	1192.4	1351.5	1513.4	1678.0	1845.3	2015.2	2187.5	2361.9	2537.6

Table A 17: Results – CIGS PV Cells – Indium – EOL-I scenarios – Low collection – Min

EOL-I scenarios – Low collection – Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1325.9	166.3	185.2	201.8	216.7	230.3	243.4	256.7	270.9	256.7	245.4	236.6	229.9	224.7	220.4	216.4	212.0	206.5	199.1
$L_{F\&M,LF}$	25.9	3.1	3.4	3.5	3.6	3.7	3.8	3.8	3.8	3.5	3.2	2.9	2.7	2.5	2.3	2.2	2.0	1.8	1.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.1	0.2	0.3	0.6	0.9	1.5	2.4	3.5	5.0	7.0	9.5	12.5	16.2	20.6	25.6	31.3	37.7	44.6
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.4	0.6	0.8	1.1	1.4	1.8	2.3	2.8	3.5	4.2	5.0
$R_{F\&M}$	113.5	14.9	17.3	19.6	21.8	24.0	26.2	28.4	30.8	30.0	29.3	28.9	28.6	28.5	28.5	28.4	28.2	27.8	27.2
$R_{F\&M,EOL}$	0.0	0.0	0.1	0.2	0.4	0.7	1.2	2.0	3.2	4.9	7.3	10.4	14.6	19.9	26.7	35.2	45.6	58.0	72.8
$Out_{MP} = In_{FM}$	729.2	92.0	103.0	112.8	121.8	130.2	138.4	146.7	155.6	148.3	142.5	138.1	134.9	132.5	130.7	129.0	127.0	124.3	120.5
$Out_{FM} = In_{Use}$	357.0	45.8	52.1	58.0	63.6	69.0	74.5	80.2	86.3	83.5	81.4	80.0	79.2	78.9	78.9	78.9	78.7	78.1	76.7
$Out_{Use} = In_{EOL}$	0.1	0.1	0.3	0.5	1.0	1.8	2.9	4.7	7.1	10.5	15.0	20.9	28.5	37.9	49.6	63.7	80.4	99.9	122.3
$L_{MP,env}$	13.3	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0
$L_{MP,omf}$	13.3	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0
$L_{MP,lf}$	570.1	71.1	78.7	85.3	91.0	96.2	101.0	105.9	111.1	104.6	99.4	95.2	92.0	89.3	87.1	84.9	82.7	80.0	76.7
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	232.9	28.2	30.2	31.7	32.7	33.4	33.9	34.3	34.6	31.3	28.6	26.3	24.3	22.5	21.0	19.5	18.0	16.5	15.0
$Stock_{Use}$	6501.4	6547.0	6598.9	6656.3	6718.9	6786.2	6857.8	6933.3	7012.5	7085.5	7151.9	7210.9	7261.7	7302.7	7332.0	7347.2	7345.6	7323.8	7278.1
$\sum R$	113.6	128.5	145.9	165.7	187.9	212.6	240.0	270.5	304.6	339.5	376.0	415.3	458.5	507.0	562.2	625.8	699.6	785.4	885.4
$\sum L_{OMF}$	246.2	276.0	308.2	342.0	377.2	413.6	451.1	489.8	529.9	568.2	605.6	643.0	681.3	721.5	764.4	810.8	861.3	916.6	977.1
$\sum L_{LF}$	596.0	670.2	752.3	841.1	935.8	1035.8	1140.8	1250.7	1366.0	1474.7	1578.0	1677.3	1773.3	1866.9	1958.6	2048.5	2136.7	2222.7	2306.0
$\sum L_{Env}$	13.3	14.9	16.6	18.5	20.4	22.4	24.4	26.5	28.6	30.5	32.3	33.9	35.5	36.9	38.2	39.5	40.7	41.8	42.8

Table A 18: Results – CIGS PV Cells – Indium – EOL-I scenarios – Low collection – Max

EOL-I scenarios – Low collection – Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	2275.7	5134.4	7617.5	9902.7	12009.5	13959.6	15777.5	17491.1	19131.4	20367.4	21617.2	22913.0	24286.2	25765.2	27372.8	29122.5	31015.0	33035.0	35147.9
$L_{F\&M,LF}$	44.4	96.6	138.2	172.9	201.6	225.1	244.2	259.4	271.5	276.3	279.9	282.7	285.0	287.2	289.3	291.2	292.8	293.8	293.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.3	0.7	1.3	2.4	4.1	6.7	10.4	15.6	22.9	32.5	44.9	60.8	80.5	104.7	133.6	167.6	206.8	251.1
$L_{EOL,lf}$	0.0	0.0	0.1	0.1	0.3	0.5	0.7	1.2	1.7	2.5	3.6	5.0	6.8	8.9	11.6	14.8	18.6	23.0	27.9
$R_{F\&M}$	194.9	460.0	711.7	962.1	1209.9	1454.7	1696.7	1936.9	2177.1	2377.3	2583.3	2798.6	3026.8	3271.5	3535.5	3820.8	4127.3	4452.9	4792.4
$R_{F\&M,EOL}$	0.1	0.2	0.4	0.8	1.7	3.1	5.4	9.0	14.5	22.4	33.7	49.3	70.6	98.9	136.0	183.7	243.9	318.6	409.9
$Out_{MP} = In_{FM}$	1251.6	2839.6	4236.2	5537.3	6752.0	7891.1	8966.9	9994.2	10989.9	11762.2	12550.0	13372.3	14247.9	15194.3	16226.0	17352.1	18574.5	19885.2	21264.5
$Out_{FM} = In_{Use}$	612.7	1413.2	2142.8	2846.2	3525.7	4184.9	4828.7	5463.5	6097.6	6622.1	7168.1	7747.0	8370.6	9050.8	9797.8	10619.5	11519.3	12494.6	13534.8
$Out_{Use} = In_{EOL}$	0.2	0.5	1.1	2.3	4.3	7.6	12.8	20.6	31.9	47.8	69.8	99.2	138.1	188.4	252.3	332.1	430.1	548.4	688.8
$L_{MP,env}$	22.8	49.9	71.9	90.8	106.8	120.2	131.5	140.9	148.8	152.8	156.1	159.1	161.9	164.6	167.3	169.9	172.3	174.4	175.7
$L_{MP,omf}$	22.8	49.9	71.9	90.8	106.8	120.2	131.5	140.9	148.8	152.8	156.1	159.1	161.9	164.6	167.3	169.9	172.3	174.4	175.7
$L_{MP,lf}$	978.5	2195.0	3237.4	4183.9	5044.0	5828.1	6547.7	7215.1	7843.9	8299.7	8755.0	9222.5	9714.5	10241.7	10812.3	11430.6	12095.8	12801.1	13531.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	399.7	869.8	1243.5	1556.1	1814.8	2026.3	2197.4	2334.4	2443.7	2486.5	2518.7	2544.0	2565.4	2584.9	2603.4	2620.7	2635.1	2644.0	2643.5
$Stock_{Use}$	10742.5	12155.1	14296.8	17140.7	20662.1	24839.3	29655.2	35098.1	41163.8	47738.1	54836.5	62484.3	70716.8	79579.1	89124.6	99412.0	110501.2	122447.4	135293.4
$\sum R$	195.0	655.2	1367.3	2330.2	3541.7	4999.5	6701.5	8647.4	10839.0	13238.7	15855.7	18703.6	21801.0	25171.3	28842.9	32847.3	37218.4	41989.9	47192.2
$\sum L_{OMF}$	422.6	1342.6	2658.7	4306.9	6230.8	8381.4	10717.0	13202.8	15810.9	18473.1	21180.4	23928.4	26716.6	29546.6	32422.0	35346.2	38321.2	41346.4	44416.7
$\sum L_{LF}$	1023.0	3314.6	6690.3	11047.2	16293.2	22346.9	29139.5	36615.1	44732.2	53310.7	62349.2	71859.3	81865.6	92403.5	103516.6	115253.2	127660.5	140778.3	154631.9
$\sum L_{Env}$	22.8	72.7	144.6	235.4	342.1	462.4	593.8	734.7	883.5	1036.3	1192.4	1351.5	1513.4	1678.0	1845.3	2015.2	2187.5	2361.9	2537.6

Table A 19: Results – CIGS PV Cells – Indium – EOL-I scenarios – High collection – Min

EOL-I scenarios – High collection – Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1325.9	166.3	185.2	201.8	216.7	230.3	243.4	256.7	270.9	256.7	245.4	236.6	229.9	224.7	220.4	216.4	212.0	206.5	199.1
$L_{F\&M,LF}$	25.9	3.1	3.4	3.5	3.6	3.7	3.8	3.8	3.8	3.5	3.2	2.9	2.7	2.5	2.3	2.2	2.0	1.8	1.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.1	0.2	0.3	0.6	0.9	1.4	2.1	3.1	4.5	6.2	8.4	11.1	14.4	18.3	23.0	28.4	34.6
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.3	0.5	0.7	0.9	1.2	1.6	2.0	2.6	3.2	3.8
$R_{F\&M}$	113.5	14.9	17.3	19.6	21.8	24.0	26.2	28.4	30.8	30.0	29.3	28.9	28.6	28.5	28.5	28.4	28.2	27.8	27.2
$R_{F\&M,EOL}$	0.0	0.1	0.2	0.3	0.6	1.1	1.9	3.1	4.7	7.0	10.1	14.1	19.2	25.6	33.6	43.3	54.8	68.3	83.9
$Out_{MP} = In_{FM}$	729.2	92.0	103.0	112.8	121.8	130.2	138.4	146.7	155.6	148.3	142.5	138.1	134.9	132.5	130.7	129.0	127.0	124.3	120.5
$Out_{FM} = In_{Use}$	357.0	45.8	52.1	58.0	63.6	69.0	74.5	80.2	86.3	83.5	81.4	80.0	79.2	78.9	78.9	78.9	78.7	78.1	76.7
$Out_{Use} = In_{EOL}$	0.1	0.1	0.3	0.5	1.0	1.8	2.9	4.7	7.1	10.5	15.0	20.9	28.5	37.9	49.6	63.7	80.4	99.9	122.3
$L_{MP,env}$	13.3	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0
$L_{MP,omf}$	13.3	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0
$L_{MP,lf}$	570.1	71.1	78.7	85.3	91.0	96.2	101.0	105.9	111.1	104.6	99.4	95.2	92.0	89.3	87.1	84.9	82.7	80.0	76.7
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	232.9	28.2	30.2	31.7	32.7	33.4	33.9	34.3	34.6	31.3	28.6	26.3	24.3	22.5	21.0	19.5	18.0	16.5	15.0
$Stock_{Use}$	6501.4	6547.0	6598.9	6656.3	6718.9	6786.2	6857.8	6933.3	7012.5	7085.5	7151.9	7210.9	7261.7	7302.7	7332.0	7347.2	7345.6	7323.8	7278.1
$\sum R$	113.6	128.6	146.0	166.0	188.4	213.5	241.6	273.1	308.7	345.6	385.0	428.0	475.8	529.9	592.0	663.7	746.7	842.8	953.9
$\sum L_{OMF}$	246.1	276.0	308.0	341.8	376.8	412.8	449.6	487.4	526.3	562.7	597.5	631.6	665.8	700.9	737.6	776.6	818.9	864.9	915.4
$\sum L_{LF}$	596.0	670.2	752.3	841.1	935.8	1035.7	1140.6	1250.5	1365.6	1474.1	1577.1	1676.0	1771.6	1864.6	1955.6	2044.7	2132.0	2217.0	2299.2
$\sum L_{Env}$	13.3	14.9	16.6	18.5	20.4	22.4	24.4	26.5	28.6	30.5	32.3	33.9	35.5	36.9	38.2	39.5	40.7	41.8	42.8

Table A 20: Results – CIGS PV Cells – Indium – EOL-I scenarios – High collection – Max

EOL-I scenarios – High collection – Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	2275.7	5134.4	7617.5	9902.7	12009.5	13959.6	15777.5	17491.1	19131.4	20367.4	21617.2	22913.0	24286.2	25765.2	27372.8	29122.5	31015.0	33035.0	35147.9
$L_{F\&M,LF}$	44.4	96.6	138.2	172.9	201.6	225.1	244.2	259.4	271.5	276.3	279.9	282.7	285.0	287.2	289.3	291.2	292.8	293.8	293.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.4	0.8	1.4	2.5	4.1	6.4	9.6	14.3	20.8	29.4	40.6	55.0	73.2	95.7	123.2	156.0	194.7
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.7	1.1	1.6	2.3	3.3	4.5	6.1	8.1	10.6	13.7	17.3	21.6
$R_{F\&M}$	194.9	460.0	711.7	962.1	1209.9	1454.7	1696.7	1936.9	2177.1	2377.3	2583.3	2798.6	3026.8	3271.5	3535.5	3820.8	4127.3	4452.9	4792.4
$R_{F\&M,EOL}$	0.1	0.3	0.7	1.4	2.7	4.9	8.3	13.5	21.2	31.9	46.7	66.6	93.0	127.3	171.0	225.7	293.2	375.0	472.5
$Out_{MP} = In_{FM}$	1251.6	2839.6	4236.2	5537.3	6752.0	7891.1	8966.9	9994.2	10989.9	11762.2	12550.0	13372.3	14247.9	15194.3	16226.0	17352.1	18574.5	19885.2	21264.5
$Out_{FM} = In_{Use}$	612.7	1413.2	2142.8	2846.2	3525.7	4184.9	4828.7	5463.5	6097.6	6622.1	7168.1	7747.0	8370.6	9050.8	9797.8	10619.5	11519.3	12494.6	13534.8
$Out_{Use} = In_{EOL}$	0.2	0.5	1.1	2.3	4.3	7.6	12.8	20.6	31.9	47.8	69.8	99.2	138.1	188.4	252.3	332.1	430.1	548.4	688.8
$L_{MP,env}$	22.8	49.9	71.9	90.8	106.8	120.2	131.5	140.9	148.8	152.8	156.1	159.1	161.9	164.6	167.3	169.9	172.3	174.4	175.7
$L_{MP,omf}$	22.8	49.9	71.9	90.8	106.8	120.2	131.5	140.9	148.8	152.8	156.1	159.1	161.9	164.6	167.3	169.9	172.3	174.4	175.7
$L_{MP,lf}$	978.5	2195.0	3237.4	4183.9	5044.0	5828.1	6547.7	7215.1	7843.9	8299.7	8755.0	9222.5	9714.5	10241.7	10812.3	11430.6	12095.8	12801.1	13531.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	399.7	869.8	1243.5	1556.1	1814.8	2026.3	2197.4	2334.4	2443.7	2486.5	2518.7	2544.0	2565.4	2584.9	2603.4	2620.7	2635.1	2644.0	2643.5
$Stock_{Use}$	10742.5	12155.1	14296.8	17140.7	20662.1	24839.3	29655.2	35098.1	41163.8	47738.1	54836.5	62484.3	70716.8	79579.1	89124.6	99412.0	110501.2	122447.4	135293.4
$\sum R$	195.0	655.4	1367.8	2331.3	3543.9	5003.4	6708.4	8658.8	10857.1	13266.2	15896.2	18761.4	21881.2	25279.9	28986.4	33032.9	37453.5	42281.4	47546.3
$\sum L_{OMF}$	422.5	1342.4	2658.2	4305.9	6228.9	8377.9	10710.8	13192.6	15794.7	18448.3	21143.9	23876.4	26644.3	29448.9	32292.8	35179.1	38109.7	41084.1	44098.0
$\sum L_{LF}$	1023.0	3314.6	6690.2	11047.1	16292.9	22346.5	29138.8	36613.9	44730.4	53308.0	62345.1	71853.6	81857.6	92392.6	103502.3	115234.7	127637.0	140749.2	154596.5
$\sum L_{Env}$	22.8	72.7	144.6	235.4	342.1	462.4	593.8	734.7	883.5	1036.3	1192.4	1351.5	1513.4	1678.0	1845.3	2015.2	2187.5	2361.9	2537.6

Table A 21: Results – CIGS PV Cells – Indium – EOL-II scenarios – No recycling – Min

EOL-II scenarios – No recycling – Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1325.9	166.3	185.2	201.8	216.7	230.3	243.4	256.7	270.9	256.7	245.4	236.6	229.9	224.7	220.4	216.4	212.0	206.5	199.1
$L_{F\&M,LF}$	25.9	3.1	3.4	3.5	3.6	3.7	3.8	3.8	3.8	3.5	3.2	2.9	2.7	2.5	2.3	2.2	2.0	1.8	1.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.1	0.2	0.5	0.9	1.6	2.6	4.2	6.4	9.4	13.5	18.8	25.6	34.1	44.6	57.3	72.3	89.9	110.1
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.5	0.7	1.0	1.5	2.1	2.8	3.8	5.0	6.4	8.0	10.0	12.2
$R_{F\&M}$	113.5	14.9	17.3	19.6	21.8	24.0	26.2	28.4	30.8	30.0	29.3	28.9	28.6	28.5	28.5	28.4	28.2	27.8	27.2
$R_{F\&M,EOL}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	729.2	92.0	103.0	112.8	121.8	130.2	138.4	146.7	155.6	148.3	142.5	138.1	134.9	132.5	130.7	129.0	127.0	124.3	120.5
$Out_{FM} = In_{Use}$	357.0	45.8	52.1	58.0	63.6	69.0	74.5	80.2	86.3	83.5	81.4	80.0	79.2	78.9	78.9	78.9	78.7	78.1	76.7
$Out_{Use} = In_{EOL}$	0.1	0.1	0.3	0.5	1.0	1.8	2.9	4.7	7.1	10.5	15.0	20.9	28.5	37.9	49.6	63.7	80.4	99.9	122.3
$L_{MP,env}$	13.3	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0
$L_{MP,omf}$	13.3	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0
$L_{MP,lf}$	570.1	71.1	78.7	85.3	91.0	96.2	101.0	105.9	111.1	104.6	99.4	95.2	92.0	89.3	87.1	84.9	82.7	80.0	76.7
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	232.9	28.2	30.2	31.7	32.7	33.4	33.9	34.3	34.6	31.3	28.6	26.3	24.3	22.5	21.0	19.5	18.0	16.5	15.0
$Stock_{Use}$	6501.4	6547.0	6598.9	6656.3	6718.9	6786.2	6857.8	6933.3	7012.5	7085.5	7151.9	7210.9	7261.7	7302.7	7332.0	7347.2	7345.6	7323.8	7278.1
$\sum R$	113.5	128.4	145.7	165.4	187.2	211.2	237.4	265.8	296.6	326.6	355.9	384.8	413.5	442.0	470.4	498.8	527.1	554.9	582.0
$\sum L_{OMF}$	246.2	276.1	308.3	342.3	377.9	414.9	453.5	494.0	537.1	579.8	623.7	670.5	721.9	780.0	847.0	925.0	1016.5	1124.0	1250.1
$\sum L_{LF}$	596.0	670.3	752.3	841.2	935.9	1036.0	1141.0	1251.2	1366.8	1476.0	1580.1	1680.3	1777.8	1873.4	1967.8	2061.2	2153.9	2245.8	2336.3
$\sum L_{Env}$	13.3	14.9	16.6	18.5	20.4	22.4	24.4	26.5	28.6	30.5	32.3	33.9	35.5	36.9	38.2	39.5	40.7	41.8	42.8

Table A 22: Results – CIGS PV Cells – Indium – EOL-II scenarios – No recycling – Max

EOL-II scenarios – No recycling – Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	2275.7	5134.4	7617.5	9902.7	12009.5	13959.6	15777.5	17491.1	19131.4	20367.4	21617.2	22913.0	24286.2	25765.2	27372.8	29122.5	31015.0	33035.0	35147.9
$L_{F\&M,LF}$	44.4	96.6	138.2	172.9	201.6	225.1	244.2	259.4	271.5	276.3	279.9	282.7	285.0	287.2	289.3	291.2	292.8	293.8	293.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.2	0.5	1.0	2.1	3.9	6.8	11.5	18.5	28.7	43.1	62.8	89.3	124.3	169.6	227.1	298.9	387.1	493.5	620.0
$L_{EOL,lf}$	0.0	0.1	0.1	0.2	0.4	0.8	1.3	2.1	3.2	4.8	7.0	9.9	13.8	18.8	25.2	33.2	43.0	54.8	68.9
$R_{F\&M}$	194.9	460.0	711.7	962.1	1209.9	1454.7	1696.7	1936.9	2177.1	2377.3	2583.3	2798.6	3026.8	3271.5	3535.5	3820.8	4127.3	4452.9	4792.4
$R_{F\&M,EOL}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	1251.6	2839.6	4236.2	5537.3	6752.0	7891.1	8966.9	9994.2	10989.9	11762.2	12550.0	13372.3	14247.9	15194.3	16226.0	17352.1	18574.5	19885.2	21264.5
$Out_{FM} = In_{Use}$	612.7	1413.2	2142.8	2846.2	3525.7	4184.9	4828.7	5463.5	6097.6	6622.1	7168.1	7747.0	8370.6	9050.8	9797.8	10619.5	11519.3	12494.6	13534.8
$Out_{Use} = In_{EOL}$	0.2	0.5	1.1	2.3	4.3	7.6	12.8	20.6	31.9	47.8	69.8	99.2	138.1	188.4	252.3	332.1	430.1	548.4	688.8
$L_{MP,env}$	22.8	49.9	71.9	90.8	106.8	120.2	131.5	140.9	148.8	152.8	156.1	159.1	161.9	164.6	167.3	169.9	172.3	174.4	175.7
$L_{MP,omf}$	22.8	49.9	71.9	90.8	106.8	120.2	131.5	140.9	148.8	152.8	156.1	159.1	161.9	164.6	167.3	169.9	172.3	174.4	175.7
$L_{MP,lf}$	978.5	2195.0	3237.4	4183.9	5044.0	5828.1	6547.7	7215.1	7843.9	8299.7	8755.0	9222.5	9714.5	10241.7	10812.3	11430.6	12095.8	12801.1	13531.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	399.7	869.8	1243.5	1556.1	1814.8	2026.3	2197.4	2334.4	2443.7	2486.5	2518.7	2544.0	2565.4	2584.9	2603.4	2620.7	2635.1	2644.0	2643.5
$Stock_{Use}$	10742.5	12155.1	14296.8	17140.7	20662.1	24839.3	29655.2	35098.1	41163.8	47738.1	54836.5	62484.3	70716.8	79579.1	89124.6	99412.0	110501.2	122447.4	135293.4
$\sum R$	194.9	654.9	1366.7	2328.7	3538.6	4993.3	6689.9	8626.8	10803.9	13181.2	15764.5	18563.1	21589.9	24861.3	28396.8	32217.6	36344.9	40797.8	45590.2
$\sum L_{OMF}$	422.6	1342.8	2659.2	4308.2	6233.6	8387.0	10727.4	13221.3	15842.5	18524.8	21262.5	24054.9	26906.6	29825.6	32823.4	35912.9	39107.4	42419.3	45858.5
$\sum L_{LF}$	1023.0	3314.6	6690.4	11047.4	16293.5	22347.5	29140.6	36617.1	44735.7	53316.5	62358.3	71873.4	81886.7	92434.5	103561.2	115316.2	127747.8	140897.5	154792.1
$\sum L_{Env}$	22.8	72.7	144.6	235.4	342.1	462.4	593.8	734.7	883.5	1036.3	1192.4	1351.5	1513.4	1678.0	1845.3	2015.2	2187.5	2361.9	2537.6

Table A 23: Results – CIGS PV Cells – Indium – EOL-II scenarios – High efficiency recycling – Min

EOL-II scenarios – High efficiency recycling – Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1325.9	166.3	185.2	201.8	216.7	230.3	243.4	256.7	270.9	256.7	245.4	236.6	229.9	224.7	220.4	216.4	212.0	206.5	199.1
$L_{F\&M,LF}$	25.9	3.1	3.4	3.5	3.6	3.7	3.8	3.8	3.8	3.5	3.2	2.9	2.7	2.5	2.3	2.2	2.0	1.8	1.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.1	0.1	0.2	0.3	0.5	0.8	1.2	1.7	2.3	3.1	4.0	5.0	6.0	7.2	8.4	9.6	10.7
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.3	0.3	0.4	0.6	0.7	0.8	0.9	1.1	1.2
$R_{F\&M}$	113.5	14.9	17.3	19.6	21.8	24.0	26.2	28.4	30.8	30.0	29.3	28.9	28.6	28.5	28.5	28.4	28.2	27.8	27.2
$R_{F\&M,EOL}$	0.0	0.1	0.2	0.4	0.8	1.4	2.3	3.7	5.7	8.6	12.4	17.5	24.1	32.4	42.9	55.6	71.0	89.2	110.4
$Out_{MP} = In_{FM}$	729.2	92.0	103.0	112.8	121.8	130.2	138.4	146.7	155.6	148.3	142.5	138.1	134.9	132.5	130.7	129.0	127.0	124.3	120.5
$Out_{FM} = In_{Use}$	357.0	45.8	52.1	58.0	63.6	69.0	74.5	80.2	86.3	83.5	81.4	80.0	79.2	78.9	78.9	78.9	78.7	78.1	76.7
$Out_{Use} = In_{EOL}$	0.1	0.1	0.3	0.5	1.0	1.8	2.9	4.7	7.1	10.5	15.0	20.9	28.5	37.9	49.6	63.7	80.4	99.9	122.3
$L_{MP,env}$	13.3	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0
$L_{MP,omf}$	13.3	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0
$L_{MP,lf}$	570.1	71.1	78.7	85.3	91.0	96.2	101.0	105.9	111.1	104.6	99.4	95.2	92.0	89.3	87.1	84.9	82.7	80.0	76.7
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	232.9	28.2	30.2	31.7	32.7	33.4	33.9	34.3	34.6	31.3	28.6	26.3	24.3	22.5	21.0	19.5	18.0	16.5	15.0
$Stock_{Use}$	6501.4	6547.0	6598.9	6656.3	6718.9	6786.2	6857.8	6933.3	7012.5	7085.5	7151.9	7210.9	7261.7	7302.7	7332.0	7347.2	7345.6	7323.8	7278.1
$\sum R$	113.6	128.6	146.1	166.1	188.7	214.1	242.6	274.8	311.4	349.9	391.6	438.0	490.8	551.7	623.1	707.1	806.3	923.4	1060.9
$\sum L_{OMF}$	246.1	275.9	308.0	341.6	376.5	412.3	448.7	485.9	523.8	558.8	591.5	622.5	652.3	681.2	709.6	737.6	765.2	792.4	819.1
$\sum L_{LF}$	596.0	670.2	752.3	841.1	935.7	1035.7	1140.5	1250.3	1365.3	1473.6	1576.5	1675.0	1770.1	1862.4	1952.5	2040.4	2126.0	2208.9	2288.5
$\sum L_{Env}$	13.3	14.9	16.6	18.5	20.4	22.4	24.4	26.5	28.6	30.5	32.3	33.9	35.5	36.9	38.2	39.5	40.7	41.8	42.8

Table A 24: Results – CIGS PV Cells – Indium – EOL-II scenarios – High efficiency recycling – Max

EOL-II scenarios – High efficiency recycling – Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	2275.7	5134.4	7617.5	9902.7	12009.5	13959.6	15777.5	17491.1	19131.4	20367.4	21617.2	22913.0	24286.2	25765.2	27372.8	29122.5	31015.0	33035.0	35147.9
$L_{F\&M,LF}$	44.4	96.6	138.2	172.9	201.6	225.1	244.2	259.4	271.5	276.3	279.9	282.7	285.0	287.2	289.3	291.2	292.8	293.8	293.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.1	0.2	0.5	0.8	1.4	2.4	3.7	5.5	7.9	10.9	14.6	19.2	24.6	30.8	37.7	45.1	52.8	60.4
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.4	0.6	0.9	1.2	1.6	2.1	2.7	3.4	4.2	5.0	5.9	6.7
$R_{F\&M}$	194.9	460.0	711.7	962.1	1209.9	1454.7	1696.7	1936.9	2177.1	2377.3	2583.3	2798.6	3026.8	3271.5	3535.5	3820.8	4127.3	4452.9	4792.4
$R_{F\&M,EOL}$	0.2	0.4	0.9	1.8	3.4	6.0	10.2	16.5	25.8	39.1	57.7	83.0	116.8	161.1	218.1	290.3	380.0	489.7	621.7
$Out_{MP} = In_{FM}$	1251.6	2839.6	4236.2	5537.3	6752.0	7891.1	8966.9	9994.2	10989.9	11762.2	12550.0	13372.3	14247.9	15194.3	16226.0	17352.1	18574.5	19885.2	21264.5
$Out_{FM} = In_{Use}$	612.7	1413.2	2142.8	2846.2	3525.7	4184.9	4828.7	5463.5	6097.6	6622.1	7168.1	7747.0	8370.6	9050.8	9797.8	10619.5	11519.3	12494.6	13534.8
$Out_{Use} = In_{EOL}$	0.2	0.5	1.1	2.3	4.3	7.6	12.8	20.6	31.9	47.8	69.8	99.2	138.1	188.4	252.3	332.1	430.1	548.4	688.8
$L_{MP,env}$	22.8	49.9	71.9	90.8	106.8	120.2	131.5	140.9	148.8	152.8	156.1	159.1	161.9	164.6	167.3	169.9	172.3	174.4	175.7
$L_{MP,omf}$	22.8	49.9	71.9	90.8	106.8	120.2	131.5	140.9	148.8	152.8	156.1	159.1	161.9	164.6	167.3	169.9	172.3	174.4	175.7
$L_{MP,lf}$	978.5	2195.0	3237.4	4183.9	5044.0	5828.1	6547.7	7215.1	7843.9	8299.7	8755.0	9222.5	9714.5	10241.7	10812.3	11430.6	12095.8	12801.1	13531.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	399.7	869.8	1243.5	1556.1	1814.8	2026.3	2197.4	2334.4	2443.7	2486.5	2518.7	2544.0	2565.4	2584.9	2603.4	2620.7	2635.1	2644.0	2643.5
$Stock_{Use}$	10742.5	12155.1	14296.8	17140.7	20662.1	24839.3	29655.2	35098.1	41163.8	47738.1	54836.5	62484.3	70716.8	79579.1	89124.6	99412.0	110501.2	122447.4	135293.4
$\sum R$	195.1	655.5	1368.1	2332.0	3545.2	5005.9	6712.7	8666.1	10869.0	13285.3	15926.3	18807.8	21951.4	25383.9	29137.6	33248.6	37755.9	42698.5	48112.5
$\sum L_{OMF}$	422.5	1342.3	2657.9	4305.3	6227.7	8375.7	10706.9	13185.9	15784.0	18431.1	21116.9	23834.7	26581.2	29355.3	32156.8	34985.0	37837.5	40708.7	43588.4
$\sum L_{LF}$	1023.0	3314.6	6690.2	11047.1	16292.8	22346.2	29138.3	36613.2	44729.2	53306.1	62342.1	71848.9	81850.6	92382.2	103487.2	115213.1	127606.7	140707.4	154539.8
$\sum L_{Env}$	22.8	72.7	144.6	235.4	342.1	462.4	593.8	734.7	883.5	1036.3	1192.4	1351.5	1513.4	1678.0	1845.3	2015.2	2187.5	2361.9	2537.6

Results: Gallium

Table A 25: Results – CIGS PV Cells – Gallium – Baseline-Scenario – Min

Baseline-Scenario - Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	534.0	67.0	74.6	81.3	87.3	92.8	98.1	103.4	109.1	103.4	98.9	95.3	92.6	90.5	88.8	87.2	85.4	83.2	80.2
$L_{F\&M,LF}$	10.4	1.3	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.4	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.7	0.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.0	0.1	0.2	0.3	0.4	0.7	1.0	1.5	2.1	2.9	3.9	5.1	6.5	8.2	10.2	12.4	14.9
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.3	0.4	0.6	0.7	0.9	1.1	1.4	1.7
$R_{F\&M}$	45.7	6.0	7.0	7.9	8.8	9.7	10.5	11.4	12.4	12.1	11.8	11.6	11.5	11.5	11.5	11.4	11.4	11.2	10.9
$R_{F\&M,EOL}$	0.0	0.0	0.1	0.1	0.2	0.4	0.7	1.1	1.7	2.5	3.7	5.2	7.1	9.6	12.7	16.5	21.1	26.5	32.8
$Out_{MP} = In_{FM}$	293.7	37.0	41.5	45.4	49.1	52.4	55.7	59.1	62.7	59.7	57.4	55.6	54.3	53.4	52.6	51.9	51.1	50.1	48.5
$Out_{FM} = In_{Use}$	143.8	18.4	21.0	23.4	25.6	27.8	30.0	32.3	34.8	33.6	32.8	32.2	31.9	31.8	31.8	31.8	31.7	31.5	30.9
$Out_{Use} = In_{EOL}$	0.0	0.1	0.1	0.2	0.4	0.7	1.2	1.9	2.9	4.2	6.1	8.4	11.5	15.3	20.0	25.6	32.4	40.2	49.3
$L_{MP,env}$	5.3	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4
$L_{MP,omf}$	5.3	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4
$L_{MP,lf}$	229.6	28.6	31.7	34.3	36.7	38.7	40.7	42.7	44.7	42.1	40.0	38.4	37.0	36.0	35.1	34.2	33.3	32.2	30.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	93.8	11.3	12.2	12.8	13.2	13.5	13.7	13.8	13.9	12.6	11.5	10.6	9.8	9.1	8.4	7.8	7.3	6.7	6.0
$Stock_{Use}$	2618.6	2637.0	2657.9	2681.0	2706.2	2733.3	2762.2	2792.6	2824.5	2853.9	2880.6	2904.4	2924.8	2941.3	2953.2	2959.3	2958.6	2949.9	2931.5
$\sum R$	45.7	51.8	58.8	66.8	75.9	85.9	97.2	109.7	123.8	138.5	154.0	170.8	189.5	210.6	234.8	262.7	295.2	332.9	376.6
$\sum L_{OMF}$	99.1	111.2	124.1	137.7	151.8	166.3	181.2	196.6	212.4	227.3	241.7	255.8	270.1	284.9	300.4	316.9	334.8	354.3	375.6
$\sum L_{LF}$	240.1	270.0	303.0	338.8	376.9	417.2	459.4	503.7	550.1	593.8	635.3	675.2	713.8	751.3	788.0	824.0	859.3	893.6	926.8
$\sum L_{Env}$	5.3	6.0	6.7	7.4	8.2	9.0	9.8	10.7	11.5	12.3	13.0	13.7	14.3	14.9	15.4	15.9	16.4	16.8	17.2

Table A 26: Results – CIGS PV Cells – Gallium – Baseline-Scenario – Max

Baseline-Scenario - Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1676.8	3783.3	5612.9	7296.7	8849.1	10286.0	11625.5	12888.2	14096.8	15007.6	15928.5	16883.3	17895.1	18984.9	20169.4	21458.7	22853.2	24341.6	25898.5
$L_{F\&M,LF}$	32.7	71.2	101.8	127.4	148.6	165.9	179.9	191.1	200.1	203.6	206.2	208.3	210.0	211.6	213.1	214.6	215.7	216.5	216.4
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.3	0.6	1.2	2.1	3.5	5.6	8.6	12.6	18.1	25.3	34.5	46.2	60.7	78.4	99.5	124.4	153.0
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.1	0.2	0.4	0.6	1.0	1.4	2.0	2.8	3.8	5.1	6.7	8.7	11.1	13.8	17.0
$R_{F\&M}$	143.6	339.0	524.4	708.9	891.5	1071.9	1250.2	1427.2	1604.2	1751.7	1903.5	2062.1	2230.3	2410.5	2605.1	2815.3	3041.2	3281.1	3531.2
$R_{F\&M,EOL}$	0.1	0.2	0.5	1.0	1.8	3.3	5.5	9.0	14.0	21.2	31.3	45.0	63.4	87.5	118.4	157.6	206.3	265.9	337.5
$Out_{MP} = In_{FM}$	922.3	2092.4	3121.4	4080.1	4975.2	5814.5	6607.2	7364.2	8097.8	8666.9	9247.4	9853.3	10498.5	11195.8	11956.0	12785.8	13686.5	14652.3	15668.6
$Out_{FM} = In_{Use}$	451.4	1041.3	1578.9	2097.2	2597.9	3083.6	3558.0	4025.7	4492.9	4879.5	5281.8	5708.3	6167.8	6669.0	7219.4	7824.9	8487.9	9206.5	9973.0
$Out_{Use} = In_{EOL}$	0.2	0.4	0.8	1.7	3.2	5.6	9.4	15.2	23.5	35.2	51.4	73.1	101.8	138.8	185.9	244.7	316.9	404.1	507.6
$L_{MP,env}$	16.8	36.8	53.0	66.9	78.7	88.6	96.9	103.8	109.6	112.6	115.0	117.2	119.3	121.3	123.3	125.2	127.0	128.5	129.5
$L_{MP,omf}$	16.8	36.8	53.0	66.9	78.7	88.6	96.9	103.8	109.6	112.6	115.0	117.2	119.3	121.3	123.3	125.2	127.0	128.5	129.5
$L_{MP,lf}$	721.0	1617.3	2385.5	3082.9	3716.6	4294.4	4824.6	5316.4	5779.7	6115.6	6451.0	6795.5	7158.0	7546.5	7966.9	8422.5	8912.7	9432.4	9970.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	294.5	640.9	916.2	1146.6	1337.2	1493.1	1619.1	1720.1	1800.6	1832.2	1855.9	1874.5	1890.3	1904.7	1918.3	1931.0	1941.7	1948.2	1947.9
$Stock_{Use}$	7915.5	8956.4	10534.5	12630.0	15224.7	18302.7	21851.2	25861.8	30331.2	35175.4	40405.8	46041.0	52107.1	58637.2	65670.8	73251.0	81422.0	90224.4	99689.9
$\sum R$	143.7	482.9	1007.8	1717.7	2611.0	3686.1	4941.8	6377.9	7996.1	9769.0	11703.8	13810.9	16104.6	18602.6	21326.1	24299.0	27546.5	31093.5	34962.2
$\sum L_{OMF}$	311.3	989.1	1958.7	3172.9	4590.0	6173.8	7893.3	9722.8	11641.7	13599.0	15588.0	17605.1	19649.2	21721.4	23823.7	25958.3	28126.5	30327.6	32558.0
$\sum L_{LF}$	753.8	2442.3	4929.7	8140.0	12005.4	16465.9	21470.8	26978.9	32959.6	39280.2	45939.4	52946.1	60318.0	68081.2	76268.1	84913.8	94053.4	103716.0	113920.4
$\sum L_{Env}$	16.8	53.6	106.6	173.4	252.1	340.7	437.6	541.4	651.0	763.6	878.6	995.9	1115.2	1236.5	1359.7	1484.9	1611.9	1740.3	1869.8

Table A 27: Results – CIGS PV Cells – Gallium – Material production alternative (Scenario A) – Min

Material production alternative (Scenario A) - Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	466.2	58.5	65.1	71.0	76.2	81.0	85.6	90.3	95.2	90.3	86.3	83.2	80.8	79.0	77.5	76.1	74.5	72.6	70.0
$L_{F\&M,LF}$	10.4	1.3	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.4	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.7	0.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.0	0.1	0.2	0.3	0.4	0.7	1.0	1.5	2.1	2.9	3.9	5.1	6.5	8.2	10.2	12.4	14.9
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.3	0.4	0.6	0.7	0.9	1.1	1.4	1.7
$R_{F\&M}$	45.7	6.0	7.0	7.9	8.8	9.7	10.5	11.4	12.4	12.1	11.8	11.6	11.5	11.5	11.5	11.4	11.4	11.2	10.9
$R_{F\&M,EOL}$	0.0	0.0	0.1	0.1	0.2	0.4	0.7	1.1	1.7	2.5	3.7	5.2	7.1	9.6	12.7	16.5	21.1	26.5	32.8
$Out_{MP} = In_{FM}$	293.7	37.0	41.5	45.4	49.1	52.4	55.7	59.1	62.7	59.7	57.4	55.6	54.3	53.4	52.6	51.9	51.1	50.1	48.5
$Out_{FM} = In_{Use}$	143.8	18.4	21.0	23.4	25.6	27.8	30.0	32.3	34.8	33.6	32.8	32.2	31.9	31.8	31.8	31.8	31.7	31.5	30.9
$Out_{Use} = In_{EOL}$	0.0	0.1	0.1	0.2	0.4	0.7	1.2	1.9	2.9	4.2	6.1	8.4	11.5	15.3	20.0	25.6	32.4	40.2	49.3
$L_{MP,env}$	4.7	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4
$L_{MP,omf}$	4.7	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4
$L_{MP,lf}$	163.2	20.3	22.4	24.2	25.8	27.2	28.4	29.7	31.1	29.2	27.7	26.4	25.4	24.6	23.9	23.3	22.6	21.8	20.8
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	93.8	11.3	12.2	12.8	13.2	13.5	13.7	13.8	13.9	12.6	11.5	10.6	9.8	9.1	8.4	7.8	7.3	6.7	6.0
$Stock_{Use}$	2618.6	2637.0	2657.9	2681.0	2706.2	2733.3	2762.2	2792.6	2824.5	2853.9	2880.6	2904.4	2924.8	2941.3	2953.2	2959.3	2958.6	2949.9	2931.5
$\sum R$	45.7	51.8	58.8	66.8	75.9	85.9	97.2	109.7	123.8	138.5	154.0	170.8	189.5	210.6	234.8	262.7	295.2	332.9	376.6
$\sum L_{OMF}$	98.5	110.4	123.2	136.7	150.8	165.2	180.0	195.2	210.9	225.7	240.0	254.1	268.3	283.0	298.4	314.9	332.8	352.2	373.4
$\sum L_{LF}$	173.6	195.2	218.9	244.6	271.8	300.5	330.5	361.8	394.6	425.4	454.6	482.5	509.4	535.6	561.2	586.3	610.8	634.7	657.8
$\sum L_{Env}$	4.7	5.2	5.8	6.5	7.2	7.9	8.6	9.3	10.1	10.7	11.4	11.9	12.5	13.0	13.4	13.9	14.3	14.7	15.0

Table A 28: Results – CIGS PV Cells – Gallium – Material production alternative (Scenario A) – Max

Material production alternative (Scenario A) - Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1463.9	3302.9	4900.1	6370.2	7725.4	8979.9	10149.3	11251.6	12306.7	13101.9	13905.8	14739.4	15622.7	16574.1	17608.2	18733.7	19951.2	21250.6	22609.8
$L_{F\&M,LF}$	32.7	71.2	101.8	127.4	148.6	165.9	179.9	191.1	200.1	203.6	206.2	208.3	210.0	211.6	213.1	214.6	215.7	216.5	216.4
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.3	0.6	1.2	2.1	3.5	5.6	8.6	12.6	18.1	25.3	34.5	46.2	60.7	78.4	99.5	124.4	153.0
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.1	0.2	0.4	0.6	1.0	1.4	2.0	2.8	3.8	5.1	6.7	8.7	11.1	13.8	17.0
$R_{F\&M}$	143.6	339.0	524.4	708.9	891.5	1071.9	1250.2	1427.2	1604.2	1751.7	1903.5	2062.1	2230.3	2410.5	2605.1	2815.3	3041.2	3281.1	3531.2
$R_{F\&M,EOL}$	0.1	0.2	0.5	1.0	1.8	3.3	5.5	9.0	14.0	21.2	31.3	45.0	63.4	87.5	118.4	157.6	206.3	265.9	337.5
$Out_{MP} = In_{FM}$	922.3	2092.4	3121.4	4080.1	4975.2	5814.5	6607.2	7364.2	8097.8	8666.9	9247.4	9853.3	10498.5	11195.8	11956.0	12785.8	13686.5	14652.3	15668.6
$Out_{FM} = In_{Use}$	451.4	1041.3	1578.9	2097.2	2597.9	3083.6	3558.0	4025.7	4492.9	4879.5	5281.8	5708.3	6167.8	6669.0	7219.4	7824.9	8487.9	9206.5	9973.0
$Out_{Use} = In_{EOL}$	0.2	0.4	0.8	1.7	3.2	5.6	9.4	15.2	23.5	35.2	51.4	73.1	101.8	138.8	185.9	244.7	316.9	404.1	507.6
$L_{MP,env}$	14.6	32.1	46.3	58.4	68.7	77.3	84.6	90.6	95.7	98.3	100.4	102.4	104.2	105.9	107.6	109.3	110.8	112.2	113.0
$L_{MP,omf}$	14.6	32.1	46.3	58.4	68.7	77.3	84.6	90.6	95.7	98.3	100.4	102.4	104.2	105.9	107.6	109.3	110.8	112.2	113.0
$L_{MP,lf}$	512.4	1146.3	1686.2	2173.3	2612.9	3010.7	3372.9	3706.1	4017.5	4238.4	4457.6	4681.4	4915.9	5166.5	5437.0	5729.4	6043.0	6374.0	6715.1
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	294.5	640.9	916.2	1146.6	1337.2	1493.1	1619.1	1720.1	1800.6	1832.2	1855.9	1874.5	1890.3	1904.7	1918.3	1931.0	1941.7	1948.2	1947.9
$Stock_{Use}$	7915.5	8956.4	10534.5	12630.0	15224.7	18302.7	21851.2	25861.8	30331.2	35175.4	40405.8	46041.0	52107.1	58637.2	65670.8	73251.0	81422.0	90224.4	99689.9
$\sum R$	143.7	482.9	1007.8	1717.7	2611.0	3686.1	4941.8	6377.9	7996.1	9769.0	11703.8	13810.9	16104.6	18602.6	21326.1	24299.0	27546.5	31093.5	34962.2
$\sum L_{OMF}$	309.2	982.3	1945.2	3150.9	4558.0	6130.5	7837.7	9654.1	11559.0	13502.0	15476.5	17478.6	19507.6	21564.4	23651.1	25769.8	27921.8	30106.6	32320.5
$\sum L_{LF}$	545.1	1762.6	3550.6	5851.4	8613.0	11789.9	15343.1	19241.0	23459.5	27902.9	32568.8	37461.2	42591.0	47974.3	53631.3	59583.9	65853.7	72458.0	79406.5
$\sum L_{Env}$	14.6	46.8	93.0	151.4	220.1	297.4	382.0	472.6	568.4	666.6	767.0	869.4	973.6	1079.4	1187.1	1296.3	1407.2	1519.3	1632.4

Table A 29: Results – CIGS PV Cells – Gallium – Material production alternative (Scenario C) – Min

Material production alternative (Scenario C) - Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1335.1	168.4	188.5	206.6	223.0	238.4	253.3	268.6	284.9	271.4	260.9	252.8	246.9	242.6	239.2	236.1	232.5	227.5	220.6
$L_{F\&M,LF}$	10.4	1.3	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.4	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.7	0.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.0	0.1	0.2	0.3	0.4	0.7	1.0	1.5	2.1	2.9	3.9	5.1	6.5	8.2	10.2	12.4	14.9
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.3	0.4	0.6	0.7	0.9	1.1	1.4	1.7
$R_{F\&M}$	45.7	6.0	7.0	7.9	8.8	9.7	10.5	11.4	12.4	12.1	11.8	11.6	11.5	11.5	11.5	11.4	11.4	11.2	10.9
$R_{F\&M,EOL}$	0.0	0.0	0.1	0.1	0.2	0.4	0.7	1.1	1.7	2.5	3.7	5.2	7.1	9.6	12.7	16.5	21.1	26.5	32.8
$Out_{MP} = In_{FM}$	293.7	37.0	41.5	45.4	49.1	52.4	55.7	59.1	62.7	59.7	57.4	55.6	54.3	53.4	52.6	51.9	51.1	50.1	48.5
$Out_{FM} = In_{Use}$	143.8	18.4	21.0	23.4	25.6	27.8	30.0	32.3	34.8	33.6	32.8	32.2	31.9	31.8	31.8	31.8	31.7	31.5	30.9
$Out_{Use} = In_{EOL}$	0.0	0.1	0.1	0.2	0.4	0.7	1.2	1.9	2.9	4.2	6.1	8.4	11.5	15.3	20.0	25.6	32.4	40.2	49.3
$L_{MP,env}$	13.4	1.7	1.9	2.1	2.2	2.4	2.5	2.7	2.8	2.7	2.6	2.5	2.5	2.4	2.4	2.4	2.3	2.3	2.2
$L_{MP,omf}$	13.4	1.7	1.9	2.1	2.2	2.4	2.5	2.7	2.8	2.7	2.6	2.5	2.5	2.4	2.4	2.4	2.3	2.3	2.2
$L_{MP,lf}$	1014.7	128.0	143.3	157.0	169.5	181.2	192.5	204.1	216.5	206.3	198.3	192.1	187.6	184.4	181.8	179.4	176.7	172.9	167.6
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	93.8	11.3	12.2	12.8	13.2	13.5	13.7	13.8	13.9	12.6	11.5	10.6	9.8	9.1	8.4	7.8	7.3	6.7	6.0
$Stock_{Use}$	2618.6	2637.0	2657.9	2681.0	2706.2	2733.3	2762.2	2792.6	2824.5	2853.9	2880.6	2904.4	2924.8	2941.3	2953.2	2959.3	2958.6	2949.9	2931.5
$\sum R$	45.7	51.8	58.8	66.8	75.9	85.9	97.2	109.7	123.8	138.5	154.0	170.8	189.5	210.6	234.8	262.7	295.2	332.9	376.6
$\sum L_{OMF}$	107.2	120.2	134.3	149.2	164.8	180.9	197.5	214.7	232.5	249.4	265.7	281.7	297.8	314.4	331.8	350.2	369.9	391.3	414.4
$\sum L_{LF}$	1025.1	1154.3	1299.0	1457.4	1628.4	1811.1	2005.1	2210.9	2429.0	2636.9	2836.7	3030.3	3219.5	3405.4	3588.8	3770.1	3948.7	4123.7	4293.6
$\sum L_{Env}$	13.4	15.0	16.9	19.0	21.2	23.6	26.1	28.8	31.7	34.4	37.0	39.5	42.0	44.4	46.8	49.2	51.5	53.8	56.0

Table A 30: Results – CIGS PV Cells – Gallium – Material production alternative (Scenario C) – Max

Material production alternative (Scenario C) - Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	4192.1	9510.7	14188.1	18545.9	22614.4	26429.4	30032.7	33473.5	36808.3	39394.9	42033.5	44787.6	47720.2	50890.1	54345.4	58117.2	62211.4	66601.2	71220.7
$L_{F\&M,LF}$	32.7	71.2	101.8	127.4	148.6	165.9	179.9	191.1	200.1	203.6	206.2	208.3	210.0	211.6	213.1	214.6	215.7	216.5	216.4
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.3	0.6	1.2	2.1	3.5	5.6	8.6	12.6	18.1	25.3	34.5	46.2	60.7	78.4	99.5	124.4	153.0
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.1	0.2	0.4	0.6	1.0	1.4	2.0	2.8	3.8	5.1	6.7	8.7	11.1	13.8	17.0
$R_{F\&M}$	143.6	339.0	524.4	708.9	891.5	1071.9	1250.2	1427.2	1604.2	1751.7	1903.5	2062.1	2230.3	2410.5	2605.1	2815.3	3041.2	3281.1	3531.2
$R_{F\&M,EOL}$	0.1	0.2	0.5	1.0	1.8	3.3	5.5	9.0	14.0	21.2	31.3	45.0	63.4	87.5	118.4	157.6	206.3	265.9	337.5
$Out_{MP} = In_{FM}$	922.3	2092.4	3121.4	4080.1	4975.2	5814.5	6607.2	7364.2	8097.8	8666.9	9247.4	9853.3	10498.5	11195.8	11956.0	12785.8	13686.5	14652.3	15668.6
$Out_{FM} = In_{Use}$	451.4	1041.3	1578.9	2097.2	2597.9	3083.6	3558.0	4025.7	4492.9	4879.5	5281.8	5708.3	6167.8	6669.0	7219.4	7824.9	8487.9	9206.5	9973.0
$Out_{Use} = In_{EOL}$	0.2	0.4	0.8	1.7	3.2	5.6	9.4	15.2	23.5	35.2	51.4	73.1	101.8	138.8	185.9	244.7	316.9	404.1	507.6
$L_{MP,env}$	41.9	95.1	141.9	185.5	226.1	264.3	300.3	334.7	368.1	393.9	420.3	447.9	477.2	508.9	543.5	581.2	622.1	666.0	712.2
$L_{MP,omf}$	41.9	95.1	141.9	185.5	226.1	264.3	300.3	334.7	368.1	393.9	420.3	447.9	477.2	508.9	543.5	581.2	622.1	666.0	712.2
$L_{MP,lf}$	3186.0	7228.1	10783.0	14094.9	17187.0	20086.3	22824.8	25439.8	27974.3	29940.1	31945.5	34038.6	36267.4	38676.5	41302.5	44169.1	47280.6	50616.9	54127.8
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	294.5	640.9	916.2	1146.6	1337.2	1493.1	1619.1	1720.1	1800.6	1832.2	1855.9	1874.5	1890.3	1904.7	1918.3	1931.0	1941.7	1948.2	1947.9
$Stock_{Use}$	7915.5	8956.4	10534.5	12630.0	15224.7	18302.7	21851.2	25861.8	30331.2	35175.4	40405.8	46041.0	52107.1	58637.2	65670.8	73251.0	81422.0	90224.4	99689.9
$\sum R$	143.7	482.9	1007.8	1717.7	2611.0	3686.1	4941.8	6377.9	7996.1	9769.0	11703.8	13810.9	16104.6	18602.6	21326.1	24299.0	27546.5	31093.5	34962.2
$\sum L_{OMF}$	336.5	1072.6	2131.1	3463.8	5028.4	6787.9	8710.9	10771.3	12948.6	15187.3	17481.6	19829.3	22231.4	24691.2	27213.7	29804.3	32467.6	35206.2	38019.3
$\sum L_{LF}$	3218.7	10518.1	21402.9	35625.3	52960.9	73213.4	96218.5	121850.1	150025.4	180170.5	212324.2	246573.8	283055.1	321948.3	363470.8	407863.1	455370.5	506217.8	560579.0
$\sum L_{Env}$	41.9	137.0	278.9	464.4	690.5	954.8	1255.1	1589.9	1958.0	2351.9	2772.2	3220.1	3697.3	4206.2	4749.7	5330.8	5953.0	6619.0	7331.2

Table A 31: Results – CIGS PV Cells – Gallium – F&M-I scenarios – Low Efficiency – Min

F&M-I scenarios - Low Efficiency - Min – Stocks and Flows in kilograms																			
	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
In_{MP}	1089.2	137.1	153.1	167.4	180.3	192.2	203.7	215.4	227.9	216.6	207.6	200.7	195.4	191.5	188.3	185.3	181.9	177.5	171.6
$L_{F\&M,LF}$	31.6	3.9	4.2	4.5	4.7	4.9	5.1	5.2	5.3	4.9	4.6	4.3	4.0	3.8	3.6	3.4	3.2	3.0	2.8
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.0	0.1	0.2	0.3	0.4	0.7	1.0	1.5	2.1	2.9	3.9	5.1	6.5	8.2	10.2	12.4	14.9
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.3	0.4	0.6	0.7	0.9	1.1	1.4	1.7
$R_{F\&M}$	138.9	18.5	21.8	25.1	28.4	31.7	35.2	38.8	42.8	42.3	42.1	42.2	42.6	43.2	43.9	44.6	45.2	45.4	45.2
$R_{F\&M,EOL}$	0.0	0.0	0.1	0.1	0.2	0.4	0.7	1.1	1.7	2.5	3.7	5.2	7.1	9.6	12.7	16.5	21.1	26.5	32.8
$Out_{MP} = In_{FM}$	599.1	75.8	85.2	93.6	101.3	108.6	115.8	123.1	130.9	125.1	120.5	117.1	114.7	112.9	111.6	110.4	108.9	106.9	103.8
$Out_{FM} = In_{Use}$	143.8	18.4	21.0	23.4	25.6	27.8	30.0	32.3	34.8	33.6	32.8	32.2	31.9	31.8	31.8	31.8	31.7	31.5	30.9
$Out_{Use} = In_{EOL}$	0.0	0.1	0.1	0.2	0.4	0.7	1.2	1.9	2.9	4.2	6.1	8.4	11.5	15.3	20.0	25.6	32.4	40.2	49.3
$L_{MP,env}$	10.9	1.3	1.4	1.5	1.6	1.7	1.7	1.7	1.8	1.6	1.5	1.4	1.3	1.2	1.2	1.1	1.0	0.9	0.9
$L_{MP,omf}$	10.9	1.3	1.4	1.5	1.6	1.7	1.7	1.7	1.8	1.6	1.5	1.4	1.3	1.2	1.2	1.1	1.0	0.9	0.9
$L_{MP,lf}$	468.4	58.6	65.1	70.7	75.7	80.2	84.6	88.9	93.5	88.3	84.1	80.8	78.2	76.1	74.4	72.7	70.9	68.8	66.1
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	284.8	35.0	38.1	40.6	42.6	44.2	45.6	46.8	48.0	44.3	41.1	38.4	36.1	34.1	32.3	30.6	28.8	27.0	24.9
$Stock_{Use}$	2618.6	2637.0	2657.9	2681.0	2706.2	2733.3	2762.2	2792.6	2824.5	2853.9	2880.6	2904.4	2924.8	2941.3	2953.2	2959.3	2958.6	2949.9	2931.5
$\sum R$	138.9	157.4	179.3	204.5	233.2	265.3	301.2	341.1	385.6	430.4	476.2	523.7	573.4	626.3	682.9	744.0	810.3	882.2	960.2
$\sum L_{OMF}$	295.7	332.0	371.6	413.9	458.2	504.3	552.0	601.2	652.1	699.5	744.2	786.9	828.2	868.6	908.6	948.5	988.6	1028.9	1069.5
$\sum L_{LF}$	500.0	562.5	631.8	707.1	787.5	872.7	962.4	1056.5	1155.4	1248.8	1337.7	1423.0	1505.6	1586.1	1664.8	1741.8	1817.1	1890.3	1960.8
$\sum L_{Env}$	10.9	12.2	13.7	15.2	16.8	18.5	20.2	21.9	23.7	25.3	26.8	28.2	29.5	30.7	31.9	32.9	34.0	34.9	35.7

Table A 32: Results – CIGS PV Cells – Gallium – F&M-I scenarios – Low Efficiency – Max

F&M-I scenarios - Low Efficiency - Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	3420.0	7742.0	11523.2	15027.2	18279.8	21311.0	24155.7	26854.3	29452.9	31439.1	33454.7	35549.5	37772.6	40169.0	42775.0	45612.8	48685.1	51968.5	55409.6
$L_{F\&M,LF}$	99.4	219.5	318.7	405.1	480.0	544.5	600.1	648.0	689.6	713.6	735.3	755.7	775.6	795.7	816.1	837.0	857.8	877.5	894.9
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.3	0.6	1.2	2.1	3.5	5.6	8.6	12.6	18.1	25.3	34.5	46.2	60.7	78.4	99.5	124.4	153.0
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.1	0.2	0.4	0.6	1.0	1.4	2.0	2.8	3.8	5.1	6.7	8.7	11.1	13.8	17.0
$R_{F\&M}$	436.0	1045.0	1642.0	2254.2	2879.8	3518.0	4169.9	4838.7	5529.6	6140.4	6787.5	7481.8	8235.9	9062.9	9975.1	10982.7	12091.4	13300.6	14600.9
R_{EOL}	0.1	0.2	0.5	1.0	1.8	3.3	5.5	9.0	14.0	21.2	31.3	45.0	63.4	87.5	118.4	157.6	206.3	265.9	337.5
$Out_{MP} = In_{FM}$	1881.0	4281.7	6408.2	8402.7	10277.3	12046.6	13728.5	15344.3	16919.0	18156.1	19422.3	20747.1	22159.9	23688.5	25356.0	27177.7	29156.9	31282.2	33522.8
$Out_{FM} = In_{Use}$	451.4	1041.3	1578.9	2097.2	2597.9	3083.6	3558.0	4025.7	4492.9	4879.5	5281.8	5708.3	6167.8	6669.0	7219.4	7824.9	8487.9	9206.5	9973.0
$Out_{Use} = In_{EOL}$	0.2	0.4	0.8	1.7	3.2	5.6	9.4	15.2	23.5	35.2	51.4	73.1	101.8	138.8	185.9	244.7	316.9	404.1	507.6
$L_{MP,env}$	34.2	75.3	108.8	137.7	162.5	183.5	201.3	216.3	229.1	235.8	241.6	246.9	251.8	256.6	261.4	266.1	270.5	274.3	277.0
$L_{MP,omf}$	34.2	75.3	108.8	137.7	162.5	183.5	201.3	216.3	229.1	235.8	241.6	246.9	251.8	256.6	261.4	266.1	270.5	274.3	277.0
$L_{MP,lf}$	1470.6	3309.7	4897.4	6349.0	7677.5	8897.3	10024.6	11077.4	12075.7	12811.4	13549.2	14308.7	15109.0	15967.2	16896.1	17903.0	18987.2	20137.8	21332.7
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	894.2	1975.9	2868.6	3646.2	4319.7	4900.5	5400.6	5831.9	6206.8	6422.6	6617.8	6801.3	6980.5	7161.0	7345.3	7533.1	7719.9	7897.6	8054.0
$Stock_{Use}$	7915.5	8956.4	10534.5	12630.0	15224.7	18302.7	21851.2	25861.8	30331.2	35175.4	40405.8	46041.0	52107.1	58637.2	65670.8	73251.0	81422.0	90224.4	99689.9
$\sum R$	436.1	1481.4	3123.8	5379.0	8260.6	11781.9	15957.3	20804.9	26348.5	32510.2	39328.9	46855.8	55155.1	64305.5	74399.0	85539.3	97837.0	111403.4	126341.8
$\sum L_{OMF}$	928.5	2979.8	5957.5	9742.1	14225.4	19311.6	24916.9	30970.7	37415.2	44086.2	50963.7	58037.1	65304.0	72767.8	80435.3	88312.8	96402.7	104698.9	113183.0
$\sum L_{LF}$	1570.0	5099.2	10315.4	17069.5	25227.1	34669.2	45294.3	57020.3	69786.6	83313.0	97599.5	112666.7	128555.2	145323.1	163042.1	181790.9	201646.9	222676.0	244920.6
$\sum L_{Env}$	34.2	109.5	218.3	356.0	518.5	702.0	903.3	1119.7	1348.7	1584.5	1826.2	2073.0	2324.8	2581.5	2842.9	3109.0	3379.4	3653.7	3930.8

Table A 33: Results – CIGS PV Cells – Gallium – F&M-I scenarios – High Efficiency – Min

F&M-I scenarios - High Efficiency - Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	333.4	42.2	47.4	52.1	56.4	60.5	64.4	68.5	72.8	69.5	66.9	65.0	63.6	62.6	61.8	61.1	60.2	59.0	57.3
$L_{F\&M,LF}$	2.8	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.1
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.0	0.1	0.2	0.3	0.4	0.7	1.0	1.5	2.1	2.9	3.9	5.1	6.5	8.2	10.2	12.4	14.9
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.3	0.4	0.6	0.7	0.9	1.1	1.4	1.7
$R_{F\&M}$	12.1	1.6	1.8	2.1	2.3	2.5	2.7	2.9	3.1	3.0	2.9	2.8	2.8	2.7	2.7	2.6	2.6	2.5	2.3
$R_{F\&M,EOL}$	0.0	0.0	0.1	0.1	0.2	0.4	0.7	1.1	1.7	2.5	3.7	5.2	7.1	9.6	12.7	16.5	21.1	26.5	32.8
$Out_{MP} = In_{FM}$	183.4	23.3	26.4	29.1	31.7	34.2	36.6	39.1	41.8	40.1	38.9	37.9	37.3	36.9	36.6	36.4	36.1	35.5	34.7
$Out_{FM} = In_{Use}$	143.8	18.4	21.0	23.4	25.6	27.8	30.0	32.3	34.8	33.6	32.8	32.2	31.9	31.8	31.8	31.8	31.7	31.5	30.9
$Out_{Use} = In_{EOL}$	0.0	0.1	0.1	0.2	0.4	0.7	1.2	1.9	2.9	4.2	6.1	8.4	11.5	15.3	20.0	25.6	32.4	40.2	49.3
$L_{MP,env}$	3.3	0.4	0.4	0.5	0.5	0.5	0.5	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3
$L_{MP,omf}$	3.3	0.4	0.4	0.5	0.5	0.5	0.5	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3
$L_{MP,lf}$	143.4	18.0	20.1	22.0	23.7	25.2	26.7	28.2	29.8	28.3	27.1	26.2	25.4	24.9	24.4	24.0	23.5	22.9	22.1
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	24.8	3.0	3.2	3.3	3.4	3.5	3.5	3.5	3.5	3.2	2.8	2.6	2.4	2.2	2.0	1.8	1.6	1.5	1.3
$Stock_{Use}$	2618.6	2637.0	2657.9	2681.0	2706.2	2733.3	2762.2	2792.6	2824.5	2853.9	2880.6	2904.4	2924.8	2941.3	2953.2	2959.3	2958.6	2949.9	2931.5
$\sum R$	12.1	13.7	15.6	17.8	20.3	23.2	26.6	30.6	35.5	41.0	47.6	55.7	65.6	78.0	93.4	112.5	136.1	165.1	200.2
$\sum L_{OMF}$	28.1	31.5	35.2	39.1	43.2	47.5	52.0	56.7	61.8	67.0	72.5	78.4	85.1	92.8	101.6	112.0	124.1	138.3	154.7
$\sum L_{LF}$	146.1	164.5	185.0	207.4	231.5	257.2	284.3	313.0	343.4	372.2	399.9	426.7	452.8	478.5	503.8	528.9	553.7	578.2	602.0
$\sum L_{Env}$	3.3	3.7	4.2	4.7	5.2	5.7	6.2	6.8	7.3	7.9	8.4	8.8	9.2	9.6	10.0	10.4	10.7	11.0	11.3

Table A 34: Results – CIGS PV Cells – Gallium – F&M-I scenarios – High Efficiency – Max

F&M-I scenarios - High Efficiency - Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1046.9	2383.5	3567.3	4677.4	5720.3	6703.8	7637.7	8533.7	9405.7	10088.7	10786.5	11515.4	12291.5	13130.1	14043.7	15040.3	16121.7	17281.0	18501.0
$L_{F\&M,LF}$	8.6	18.8	26.7	33.3	38.6	42.9	46.2	48.7	50.5	50.9	51.0	50.9	50.6	50.2	49.7	49.2	48.4	47.5	46.4
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.3	0.6	1.2	2.1	3.5	5.6	8.6	12.6	18.1	25.3	34.5	46.2	60.7	78.4	99.5	124.4	153.0
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.1	0.2	0.4	0.6	1.0	1.4	2.0	2.8	3.8	5.1	6.7	8.7	11.1	13.8	17.0
$R_{F\&M}$	37.9	89.3	137.7	185.3	231.8	277.1	320.9	363.5	405.0	437.9	470.6	503.6	537.2	572.0	607.9	645.0	682.8	720.4	756.4
$R_{F\&M,EOL}$	0.1	0.2	0.5	1.0	1.8	3.3	5.5	9.0	14.0	21.2	31.3	45.0	63.4	87.5	118.4	157.6	206.3	265.9	337.5
$Out_{MP} = In_{FM}$	575.8	1318.2	1983.8	2615.5	3216.1	3789.5	4340.8	4876.1	5403.1	5826.2	6262.2	6720.5	7211.0	7743.1	8324.8	8961.5	9655.1	10402.2	11193.1
$Out_{FM} = In_{Use}$	451.4	1041.3	1578.9	2097.2	2597.9	3083.6	3558.0	4025.7	4492.9	4879.5	5281.8	5708.3	6167.8	6669.0	7219.4	7824.9	8487.9	9206.5	9973.0
$Out_{Use} = In_{EOL}$	0.2	0.4	0.8	1.7	3.2	5.6	9.4	15.2	23.5	35.2	51.4	73.1	101.8	138.8	185.9	244.7	316.9	404.1	507.6
$L_{MP,env}$	10.5	23.2	33.7	42.9	50.8	57.7	63.6	68.7	73.2	75.7	77.9	80.0	81.9	83.9	85.8	87.7	89.6	91.2	92.5
$L_{MP,omf}$	10.5	23.2	33.7	42.9	50.8	57.7	63.6	68.7	73.2	75.7	77.9	80.0	81.9	83.9	85.8	87.7	89.6	91.2	92.5
$L_{MP,lf}$	450.2	1018.9	1516.1	1976.2	2402.5	2798.8	3169.6	3520.2	3856.3	4111.1	4368.5	4634.9	4916.6	5219.2	5547.2	5903.3	6287.5	6696.4	7122.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	77.8	168.8	240.5	299.7	347.7	386.0	415.7	438.1	454.6	458.0	458.8	457.8	455.4	451.9	447.7	442.4	435.9	427.8	417.3
$Stock_{Use}$	7915.5	8956.4	10534.5	12630.0	15224.7	18302.7	21851.2	25861.8	30331.2	35175.4	40405.8	46041.0	52107.1	58637.2	65670.8	73251.0	81422.0	90224.4	99689.9
$\sum R$	38.0	127.6	265.7	452.0	685.6	965.9	1292.4	1664.9	2083.9	2543.0	3044.8	3593.4	4194.1	4853.5	5579.9	6382.5	7271.6	8257.9	9351.9
$\sum L_{OMF}$	88.3	280.5	555.0	898.3	1298.1	1743.8	2226.7	2739.1	3275.4	3821.7	4376.5	4939.5	5511.4	6093.4	6687.7	7296.2	7921.3	8564.6	9227.4
$\sum L_{LF}$	458.8	1496.5	3039.4	5049.0	7490.3	10332.2	13548.5	17117.9	21025.7	25189.2	29610.7	34299.3	39270.3	44544.9	50148.7	56109.8	62456.8	69214.5	76400.8
$\sum L_{Env}$	10.5	33.6	67.3	110.2	161.1	218.8	282.4	351.2	424.3	500.0	577.9	657.9	739.8	823.7	909.5	997.3	1086.8	1178.0	1270.5

Table A 35: Results – CIGS PV Cells – Gallium – F&M-II scenarios – Pessimistic – Min

F&M-II scenarios – Pessimistic - Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	534.0	67.0	74.6	81.3	87.3	92.8	98.1	103.4	109.1	103.4	98.9	95.3	92.6	90.5	88.8	87.2	85.4	83.2	80.2
$L_{F\&M,LF}$	10.6	1.3	1.4	1.5	1.5	1.6	1.6	1.7	1.7	1.6	1.4	1.3	1.3	1.2	1.1	1.1	1.0	0.9	0.9
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.0	0.1	0.2	0.3	0.4	0.7	1.0	1.5	2.1	2.9	3.9	5.1	6.5	8.2	10.2	12.4	14.9
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.3	0.4	0.6	0.7	0.9	1.1	1.4	1.7
$R_{F\&M}$	44.1	5.7	6.5	7.3	8.0	8.7	9.4	10.1	10.9	10.5	10.2	10.0	9.8	9.7	9.6	9.6	9.4	9.3	9.0
$R_{F\&M,EOL}$	0.0	0.0	0.1	0.1	0.2	0.4	0.7	1.1	1.7	2.5	3.7	5.2	7.1	9.6	12.7	16.5	21.1	26.5	32.8
$Out_{MP} = In_{FM}$	293.7	37.0	41.5	45.4	49.1	52.4	55.7	59.1	62.7	59.7	57.4	55.6	54.3	53.4	52.6	51.9	51.1	50.1	48.5
$Out_{FM} = In_{Use}$	143.8	18.4	21.0	23.4	25.6	27.8	30.0	32.3	34.8	33.6	32.8	32.2	31.9	31.8	31.8	31.8	31.7	31.5	30.9
$Out_{Use} = In_{EOL}$	0.0	0.1	0.1	0.2	0.4	0.7	1.2	1.9	2.9	4.2	6.1	8.4	11.5	15.3	20.0	25.6	32.4	40.2	49.3
$L_{MP,env}$	5.3	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4
$L_{MP,omf}$	5.3	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4
$L_{MP,lf}$	229.6	28.6	31.7	34.3	36.7	38.7	40.7	42.7	44.7	42.1	40.0	38.4	37.0	36.0	35.1	34.2	33.3	32.2	30.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	95.3	11.6	12.6	13.3	13.9	14.3	14.7	15.0	15.3	14.0	13.0	12.1	11.3	10.7	10.1	9.5	9.0	8.4	7.8
$Stock_{Use}$	2618.6	2637.0	2657.9	2681.0	2706.2	2733.3	2762.2	2792.6	2824.5	2853.9	2880.6	2904.4	2924.8	2941.3	2953.2	2959.3	2958.6	2949.9	2931.5
$\sum R$	44.1	49.8	56.4	63.8	72.1	81.2	91.3	102.5	115.1	128.2	142.0	157.2	174.1	193.5	215.8	241.9	272.4	308.2	349.9
$\sum L_{OMF}$	100.6	112.9	126.2	140.4	155.2	170.6	186.5	203.0	220.2	236.6	252.4	268.1	283.9	300.3	317.4	335.7	355.3	376.5	399.6
$\sum L_{LF}$	240.2	270.2	303.3	339.1	377.3	417.6	460.0	504.4	551.0	594.8	636.5	676.6	715.3	753.0	789.9	826.1	861.6	896.1	929.5
$\sum L_{Env}$	5.3	6.0	6.7	7.4	8.2	9.0	9.8	10.7	11.5	12.3	13.0	13.7	14.3	14.9	15.4	15.9	16.4	16.8	17.2

Table A 36: Results – CIGS PV Cells – Gallium – F&M-II scenarios – Pessimistic – Max

F&M-II scenarios – Pessimistic – Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1676.8	3783.3	5612.9	7296.7	8849.1	10286.0	11625.5	12888.2	14096.8	15007.6	15928.5	16883.3	17895.1	18984.9	20169.4	21458.7	22853.2	24341.6	25898.5
$L_{F\&M,LF}$	33.2	72.9	105.2	132.9	156.4	176.4	193.3	207.6	219.9	226.5	232.4	237.9	243.4	249.0	254.8	260.9	267.2	273.4	279.1
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.3	0.6	1.2	2.1	3.5	5.6	8.6	12.6	18.1	25.3	34.5	46.2	60.7	78.4	99.5	124.4	153.0
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.1	0.2	0.4	0.6	1.0	1.4	2.0	2.8	3.8	5.1	6.7	8.7	11.1	13.8	17.0
$R_{F\&M}$	138.4	321.6	490.5	654.4	813.0	966.7	1116.0	1261.9	1405.9	1522.5	1641.8	1765.7	1896.8	2037.1	2188.3	2351.5	2526.5	2712.0	2904.7
$R_{F\&M,EOL}$	0.1	0.2	0.5	1.0	1.8	3.3	5.5	9.0	14.0	21.2	31.3	45.0	63.4	87.5	118.4	157.6	206.3	265.9	337.5
$Out_{MP} = In_{FM}$	922.3	2092.4	3121.4	4080.1	4975.2	5814.5	6607.2	7364.2	8097.8	8666.9	9247.4	9853.3	10498.5	11195.8	11956.0	12785.8	13686.5	14652.3	15668.6
$Out_{FM} = In_{Use}$	451.4	1041.3	1578.9	2097.2	2597.9	3083.6	3558.0	4025.7	4492.9	4879.5	5281.8	5708.3	6167.8	6669.0	7219.4	7824.9	8487.9	9206.5	9973.0
$Out_{Use} = In_{EOL}$	0.2	0.4	0.8	1.7	3.2	5.6	9.4	15.2	23.5	35.2	51.4	73.1	101.8	138.8	185.9	244.7	316.9	404.1	507.6
$L_{MP,env}$	16.8	36.8	53.0	66.9	78.7	88.6	96.9	103.8	109.6	112.6	115.0	117.2	119.3	121.3	123.3	125.2	127.0	128.5	129.5
$L_{MP,omf}$	16.8	36.8	53.0	66.9	78.7	88.6	96.9	103.8	109.6	112.6	115.0	117.2	119.3	121.3	123.3	125.2	127.0	128.5	129.5
$L_{MP,lf}$	721.0	1617.3	2385.5	3082.9	3716.6	4294.4	4824.6	5316.4	5779.7	6115.6	6451.0	6795.5	7158.0	7546.5	7966.9	8422.5	8912.7	9432.4	9970.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	299.2	656.5	946.8	1195.7	1407.8	1587.7	1739.9	1868.8	1979.1	2038.4	2091.4	2141.3	2190.4	2240.8	2293.4	2348.5	2404.9	2460.4	2511.7
$Stock_{Use}$	7915.5	8956.4	10534.5	12630.0	15224.7	18302.7	21851.2	25861.8	30331.2	35175.4	40405.8	46041.0	52107.1	58637.2	65670.8	73251.0	81422.0	90224.4	99689.9
$\sum R$	138.5	460.4	951.3	1606.7	2421.5	3391.5	4513.1	5783.9	7203.8	8747.6	10420.6	12231.4	14191.7	16316.2	18622.9	21132.0	23864.8	26842.7	30084.9
$\sum L_{OMF}$	316.0	1009.4	2009.5	3272.8	4760.5	6438.9	8279.1	10257.4	12354.7	14518.3	16742.8	19026.6	21370.9	23779.2	26256.6	28808.7	31440.1	34153.3	36947.6
$\sum L_{LF}$	754.3	2444.6	4935.3	8151.1	12024.3	16495.4	21513.7	27038.3	33038.9	39382.3	46067.8	53104.0	60509.3	68309.9	76538.4	85230.6	94421.6	104141.1	114408.1
$\sum L_{Env}$	16.8	53.6	106.6	173.4	252.1	340.7	437.6	541.4	651.0	763.6	878.6	995.9	1115.2	1236.5	1359.7	1484.9	1611.9	1740.3	1869.8

Table A 37: Results – CIGS PV Cells – Gallium – F&M-II scenarios – Optimistic – Min

F&M-II scenarios – Optimistic – Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	534.0	67.0	74.6	81.3	87.3	92.8	98.1	103.4	109.1	103.4	98.9	95.3	92.6	90.5	88.8	87.2	85.4	83.2	80.2
$L_{F\&M,LF}$	10.1	1.2	1.3	1.3	1.4	1.4	1.4	1.3	1.3	1.2	1.1	1.0	0.9	0.8	0.7	0.6	0.6	0.5	0.4
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.0	0.1	0.2	0.3	0.4	0.7	1.0	1.5	2.1	2.9	3.9	5.1	6.5	8.2	10.2	12.4	14.9
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.3	0.4	0.6	0.7	0.9	1.1	1.4	1.7
$R_{F\&M}$	49.2	6.5	7.7	8.8	9.9	11.0	12.1	13.3	14.5	14.2	14.0	13.9	13.8	13.8	13.8	13.9	13.8	13.7	13.4
$R_{F\&M,EOL}$	0.0	0.0	0.1	0.1	0.2	0.4	0.7	1.1	1.7	2.5	3.7	5.2	7.1	9.6	12.7	16.5	21.1	26.5	32.8
$Out_{MP} = In_{FM}$	293.7	37.0	41.5	45.4	49.1	52.4	55.7	59.1	62.7	59.7	57.4	55.6	54.3	53.4	52.6	51.9	51.1	50.1	48.5
$Out_{FM} = In_{Use}$	143.8	18.4	21.0	23.4	25.6	27.8	30.0	32.3	34.8	33.6	32.8	32.2	31.9	31.8	31.8	31.8	31.7	31.5	30.9
$Out_{Use} = In_{EOL}$	0.0	0.1	0.1	0.2	0.4	0.7	1.2	1.9	2.9	4.2	6.1	8.4	11.5	15.3	20.0	25.6	32.4	40.2	49.3
$L_{MP,env}$	5.3	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4
$L_{MP,omf}$	5.3	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4
$L_{MP,lf}$	229.6	28.6	31.7	34.3	36.7	38.7	40.7	42.7	44.7	42.1	40.0	38.4	37.0	36.0	35.1	34.2	33.3	32.2	30.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	90.7	10.9	11.5	11.9	12.2	12.2	12.2	12.1	12.1	10.7	9.6	8.6	7.7	7.0	6.3	5.7	5.0	4.4	3.8
$Stock_{Use}$	2618.6	2637.0	2657.9	2681.0	2706.2	2733.3	2762.2	2792.6	2824.5	2853.9	2880.6	2904.4	2924.8	2941.3	2953.2	2959.3	2958.6	2949.9	2931.5
$\sum R$	49.2	55.8	63.5	72.5	82.7	94.1	107.0	121.3	137.6	154.3	172.0	191.0	212.0	235.4	262.0	292.3	327.2	367.4	413.6
$\sum L_{OMF}$	96.0	107.6	119.8	132.6	145.7	159.0	172.4	186.1	200.1	213.1	225.5	237.6	249.9	262.5	275.9	290.3	306.0	323.2	342.3
$\sum L_{LF}$	239.7	269.6	302.5	338.2	376.2	416.4	458.5	502.5	548.7	592.2	633.5	673.2	711.5	748.8	785.3	821.1	856.1	890.2	923.1
$\sum L_{Env}$	5.3	6.0	6.7	7.4	8.2	9.0	9.8	10.7	11.5	12.3	13.0	13.7	14.3	14.9	15.4	15.9	16.4	16.8	17.2

Table A 38: Results – CIGS PV Cells – Gallium – F&M-II scenarios – Optimistic – Max

F&M-II scenarios – Optimistic – Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1676.8	3783.3	5612.9	7296.7	8849.1	10286.0	11625.5	12888.2	14096.8	15007.6	15928.5	16883.3	17895.1	18984.9	20169.4	21458.7	22853.2	24341.6	25898.5
$L_{F\&M,LF}$	31.6	68.1	96.3	119.0	136.9	150.7	161.0	168.3	173.0	172.7	171.3	169.1	166.3	163.0	159.1	154.8	149.7	143.8	136.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.3	0.6	1.2	2.1	3.5	5.6	8.6	12.6	18.1	25.3	34.5	46.2	60.7	78.4	99.5	124.4	153.0
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.1	0.2	0.4	0.6	1.0	1.4	2.0	2.8	3.8	5.1	6.7	8.7	11.1	13.8	17.0
$R_{F\&M}$	154.4	370.0	580.0	793.2	1008.0	1223.4	1439.2	1655.9	1874.5	2060.4	2252.5	2453.8	2667.7	2897.2	3145.1	3413.1	3701.4	4008.1	4328.6
$R_{F\&M,EOL}$	0.1	0.2	0.5	1.0	1.8	3.3	5.5	9.0	14.0	21.2	31.3	45.0	63.4	87.5	118.4	157.6	206.3	265.9	337.5
$Out_{MP} = In_{FM}$	922.3	2092.4	3121.4	4080.1	4975.2	5814.5	6607.2	7364.2	8097.8	8666.9	9247.4	9853.3	10498.5	11195.8	11956.0	12785.8	13686.5	14652.3	15668.6
$Out_{FM} = In_{Use}$	451.4	1041.3	1578.9	2097.2	2597.9	3083.6	3558.0	4025.7	4492.9	4879.5	5281.8	5708.3	6167.8	6669.0	7219.4	7824.9	8487.9	9206.5	9973.0
$Out_{Use} = In_{EOL}$	0.2	0.4	0.8	1.7	3.2	5.6	9.4	15.2	23.5	35.2	51.4	73.1	101.8	138.8	185.9	244.7	316.9	404.1	507.6
$L_{MP,env}$	16.8	36.8	53.0	66.9	78.7	88.6	96.9	103.8	109.6	112.6	115.0	117.2	119.3	121.3	123.3	125.2	127.0	128.5	129.5
$L_{MP,omf}$	16.8	36.8	53.0	66.9	78.7	88.6	96.9	103.8	109.6	112.6	115.0	117.2	119.3	121.3	123.3	125.2	127.0	128.5	129.5
$L_{MP,lf}$	721.0	1617.3	2385.5	3082.9	3716.6	4294.4	4824.6	5316.4	5779.7	6115.6	6451.0	6795.5	7158.0	7546.5	7966.9	8422.5	8912.7	9432.4	9970.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	284.7	613.0	866.3	1070.8	1232.4	1356.7	1449.0	1514.3	1557.3	1554.4	1541.8	1522.0	1496.7	1466.7	1432.3	1393.0	1347.5	1293.9	1230.2
$Stock_{Use}$	7915.5	8956.4	10534.5	12630.0	15224.7	18302.7	21851.2	25861.8	30331.2	35175.4	40405.8	46041.0	52107.1	58637.2	65670.8	73251.0	81422.0	90224.4	99689.9
$\sum R$	154.5	524.7	1105.2	1899.3	2909.1	4135.8	5580.5	7245.4	9133.9	11215.5	13499.2	15998.1	18729.1	21713.8	24977.3	28548.0	32455.7	36729.6	41395.7
$\sum L_{OMF}$	301.6	951.5	1871.1	3009.4	4321.7	5769.0	7318.4	8942.1	10617.6	12297.2	13972.1	15636.7	17287.2	18921.4	20537.7	22134.3	23708.3	25255.0	26767.8
$\sum L_{LF}$	752.7	2438.2	4919.9	8121.8	11975.5	16420.9	21406.9	26892.2	32845.8	39135.5	45759.9	52727.3	60055.5	67770.1	75902.9	84489.0	93562.5	103152.4	113277.0
$\sum L_{Env}$	16.8	53.6	106.6	173.4	252.1	340.7	437.6	541.4	651.0	763.6	878.6	995.9	1115.2	1236.5	1359.7	1484.9	1611.9	1740.3	1869.8

Table A 39: Results – CIGS PV Cells – Gallium – EOL-I scenarios – Low collection – Min

EOL-I scenarios – Low collection – Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	534.0	67.0	74.6	81.3	87.3	92.8	98.1	103.4	109.1	103.4	98.9	95.3	92.6	90.5	88.8	87.2	85.4	83.2	80.2
$L_{F\&M,LF}$	10.4	1.3	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.4	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.7	0.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.1	0.1	0.2	0.4	0.6	1.0	1.4	2.0	2.8	3.8	5.0	6.5	8.3	10.3	12.6	15.2	18.0
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.3	0.4	0.6	0.7	0.9	1.1	1.4	1.7	2.0
$R_{F\&M}$	45.7	6.0	7.0	7.9	8.8	9.7	10.5	11.4	12.4	12.1	11.8	11.6	11.5	11.5	11.5	11.4	11.4	11.2	10.9
$R_{F\&M,EOL}$	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.8	1.3	2.0	2.9	4.2	5.9	8.0	10.8	14.2	18.4	23.4	29.3
$Out_{MP} = In_{FM}$	293.7	37.0	41.5	45.4	49.1	52.4	55.7	59.1	62.7	59.7	57.4	55.6	54.3	53.4	52.6	51.9	51.1	50.1	48.5
$Out_{FM} = In_{Use}$	143.8	18.4	21.0	23.4	25.6	27.8	30.0	32.3	34.8	33.6	32.8	32.2	31.9	31.8	31.8	31.8	31.7	31.5	30.9
$Out_{Use} = In_{EOL}$	0.0	0.1	0.1	0.2	0.4	0.7	1.2	1.9	2.9	4.2	6.1	8.4	11.5	15.3	20.0	25.6	32.4	40.2	49.3
$L_{MP,env}$	5.3	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4
$L_{MP,omf}$	5.3	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4
$L_{MP,lf}$	229.6	28.6	31.7	34.3	36.7	38.7	40.7	42.7	44.7	42.1	40.0	38.4	37.0	36.0	35.1	34.2	33.3	32.2	30.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	93.8	11.3	12.2	12.8	13.2	13.5	13.7	13.8	13.9	12.6	11.5	10.6	9.8	9.1	8.4	7.8	7.3	6.7	6.0
$Stock_{Use}$	2618.6	2637.0	2657.9	2681.0	2706.2	2733.3	2762.2	2792.6	2824.5	2853.9	2880.6	2904.4	2924.8	2941.3	2953.2	2959.3	2958.6	2949.9	2931.5
$\sum R$	45.7	51.8	58.8	66.7	75.7	85.6	96.7	109.0	122.7	136.7	151.5	167.3	184.7	204.2	226.4	252.0	281.8	316.4	356.6
$\sum L_{OMF}$	99.1	111.2	124.1	137.8	151.9	166.6	181.7	197.3	213.5	228.9	243.9	259.0	274.4	290.6	307.9	326.6	346.9	369.2	393.6
$\sum L_{LF}$	240.1	270.0	303.0	338.8	376.9	417.2	459.5	503.8	550.2	594.0	635.6	675.6	714.2	751.9	788.9	825.1	860.6	895.3	928.8
$\sum L_{Env}$	5.3	6.0	6.7	7.4	8.2	9.0	9.8	10.7	11.5	12.3	13.0	13.7	14.3	14.9	15.4	15.9	16.4	16.8	17.2

Table A 40: Results – CIGS PV Cells – Gallium – EOL-I scenarios – Low collection – Max

EOL-I scenarios – Low collection – Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1676.8	3783.3	5612.9	7296.7	8849.1	10286.0	11625.5	12888.2	14096.8	15007.6	15928.5	16883.3	17895.1	18984.9	20169.4	21458.7	22853.2	24341.6	25898.5
$L_{F\&M,LF}$	32.7	71.2	101.8	127.4	148.6	165.9	179.9	191.1	200.1	203.6	206.2	208.3	210.0	211.6	213.1	214.6	215.7	216.5	216.4
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.2	0.5	1.0	1.8	3.0	4.9	7.7	11.5	16.8	23.9	33.1	44.8	59.3	77.1	98.4	123.5	152.4	185.0
$L_{EOL,lf}$	0.0	0.0	0.1	0.1	0.2	0.3	0.5	0.9	1.3	1.9	2.7	3.7	5.0	6.6	8.6	10.9	13.7	16.9	20.6
$R_{F\&M}$	143.6	339.0	524.4	708.9	891.5	1071.9	1250.2	1427.2	1604.2	1751.7	1903.5	2062.1	2230.3	2410.5	2605.1	2815.3	3041.2	3281.1	3531.2
$R_{F\&M,EOL}$	0.1	0.1	0.3	0.6	1.2	2.3	4.0	6.6	10.7	16.5	24.8	36.3	52.0	72.9	100.2	135.3	179.7	234.8	302.0
$Out_{MP} = In_{FM}$	922.3	2092.4	3121.4	4080.1	4975.2	5814.5	6607.2	7364.2	8097.8	8666.9	9247.4	9853.3	10498.5	11195.8	11956.0	12785.8	13686.5	14652.3	15668.6
$Out_{FM} = In_{Use}$	451.4	1041.3	1578.9	2097.2	2597.9	3083.6	3558.0	4025.7	4492.9	4879.5	5281.8	5708.3	6167.8	6669.0	7219.4	7824.9	8487.9	9206.5	9973.0
$Out_{Use} = In_{EOL}$	0.2	0.4	0.8	1.7	3.2	5.6	9.4	15.2	23.5	35.2	51.4	73.1	101.8	138.8	185.9	244.7	316.9	404.1	507.6
$L_{MP,env}$	16.8	36.8	53.0	66.9	78.7	88.6	96.9	103.8	109.6	112.6	115.0	117.2	119.3	121.3	123.3	125.2	127.0	128.5	129.5
$L_{MP,omf}$	16.8	36.8	53.0	66.9	78.7	88.6	96.9	103.8	109.6	112.6	115.0	117.2	119.3	121.3	123.3	125.2	127.0	128.5	129.5
$L_{MP,lf}$	721.0	1617.3	2385.5	3082.9	3716.6	4294.4	4824.6	5316.4	5779.7	6115.6	6451.0	6795.5	7158.0	7546.5	7966.9	8422.5	8912.7	9432.4	9970.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	294.5	640.9	916.2	1146.6	1337.2	1493.1	1619.1	1720.1	1800.6	1832.2	1855.9	1874.5	1890.3	1904.7	1918.3	1931.0	1941.7	1948.2	1947.9
$Stock_{Use}$	7915.5	8956.4	10534.5	12630.0	15224.7	18302.7	21851.2	25861.8	30331.2	35175.4	40405.8	46041.0	52107.1	58637.2	65670.8	73251.0	81422.0	90224.4	99689.9
$\sum R$	143.7	482.7	1007.5	1717.0	2609.7	3683.8	4938.0	6371.8	7986.6	9754.9	11683.2	13781.6	16063.9	18547.3	21252.6	24203.3	27424.1	30940.0	34773.2
$\sum L_{OMF}$	311.4	989.3	1959.0	3173.5	4591.1	6175.8	7896.7	9728.4	11650.2	13611.7	15606.6	17631.5	19685.9	21771.2	23889.9	26044.5	28236.7	30465.7	32728.1
$\sum L_{LF}$	753.8	2442.4	4929.7	8140.1	12005.5	16466.1	21471.2	26979.5	32960.6	39281.6	45941.5	52949.0	60322.0	68086.8	76275.4	84923.4	94065.6	103731.4	113939.3
$\sum L_{Env}$	16.8	53.6	106.6	173.4	252.1	340.7	437.6	541.4	651.0	763.6	878.6	995.9	1115.2	1236.5	1359.7	1484.9	1611.9	1740.3	1869.8

Table A 41: Results – CIGS PV Cells – Gallium – EOL-I scenarios – High collection – Min

EOL-I scenarios – High collection – Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	534.0	67.0	74.6	81.3	87.3	92.8	98.1	103.4	109.1	103.4	98.9	95.3	92.6	90.5	88.8	87.2	85.4	83.2	80.2
$L_{F\&M,LF}$	10.4	1.3	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.4	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.7	0.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.0	0.1	0.1	0.2	0.4	0.6	0.9	1.3	1.8	2.5	3.4	4.5	5.8	7.4	9.3	11.4	13.9
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.3	0.4	0.5	0.6	0.8	1.0	1.3	1.5
$R_{F\&M}$	45.7	6.0	7.0	7.9	8.8	9.7	10.5	11.4	12.4	12.1	11.8	11.6	11.5	11.5	11.5	11.4	11.4	11.2	10.9
$R_{F\&M,EOL}$	0.0	0.0	0.1	0.1	0.3	0.5	0.8	1.2	1.9	2.8	4.0	5.7	7.7	10.3	13.5	17.4	22.1	27.5	33.8
$Out_{MP} = In_{FM}$	293.7	37.0	41.5	45.4	49.1	52.4	55.7	59.1	62.7	59.7	57.4	55.6	54.3	53.4	52.6	51.9	51.1	50.1	48.5
$Out_{FM} = In_{Use}$	143.8	18.4	21.0	23.4	25.6	27.8	30.0	32.3	34.8	33.6	32.8	32.2	31.9	31.8	31.8	31.8	31.7	31.5	30.9
$Out_{Use} = In_{EOL}$	0.0	0.1	0.1	0.2	0.4	0.7	1.2	1.9	2.9	4.2	6.1	8.4	11.5	15.3	20.0	25.6	32.4	40.2	49.3
$L_{MP,env}$	5.3	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4
$L_{MP,omf}$	5.3	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4
$L_{MP,lf}$	229.6	28.6	31.7	34.3	36.7	38.7	40.7	42.7	44.7	42.1	40.0	38.4	37.0	36.0	35.1	34.2	33.3	32.2	30.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	93.8	11.3	12.2	12.8	13.2	13.5	13.7	13.8	13.9	12.6	11.5	10.6	9.8	9.1	8.4	7.8	7.3	6.7	6.0
$Stock_{Use}$	2618.6	2637.0	2657.9	2681.0	2706.2	2733.3	2762.2	2792.6	2824.5	2853.9	2880.6	2904.4	2924.8	2941.3	2953.2	2959.3	2958.6	2949.9	2931.5
$\sum R$	45.7	51.8	58.8	66.8	75.9	86.0	97.3	110.0	124.3	139.2	155.1	172.4	191.6	213.5	238.4	267.3	300.7	339.5	384.2
$\sum L_{OMF}$	99.1	111.2	124.1	137.7	151.8	166.3	181.1	196.3	212.0	226.6	240.7	254.4	268.2	282.3	297.1	312.8	329.8	348.4	368.7
$\sum L_{LF}$	240.1	270.0	303.0	338.8	376.9	417.2	459.4	503.7	550.0	593.7	635.2	675.1	713.5	751.0	787.7	823.6	858.7	893.0	926.0
$\sum L_{Env}$	5.3	6.0	6.7	7.4	8.2	9.0	9.8	10.7	11.5	12.3	13.0	13.7	14.3	14.9	15.4	15.9	16.4	16.8	17.2

Table A 42: Results – CIGS PV Cells – Gallium – EOL-I scenarios – High collection – Max

EOL-I scenarios – High collection – Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1676.8	3783.3	5612.9	7296.7	8849.1	10286.0	11625.5	12888.2	14096.8	15007.6	15928.5	16883.3	17895.1	18984.9	20169.4	21458.7	22853.2	24341.6	25898.5
$L_{F\&M,LF}$	32.7	71.2	101.8	127.4	148.6	165.9	179.9	191.1	200.1	203.6	206.2	208.3	210.0	211.6	213.1	214.6	215.7	216.5	216.4
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.1	0.1	0.3	0.6	1.1	1.8	3.0	4.7	7.1	10.6	15.3	21.6	29.9	40.5	53.9	70.5	90.8	115.0	143.4
$L_{EOL,lf}$	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.5	0.8	1.2	1.7	2.4	3.3	4.5	6.0	7.8	10.1	12.8	15.9
$R_{F\&M}$	143.6	339.0	524.4	708.9	891.5	1071.9	1250.2	1427.2	1604.2	1751.7	1903.5	2062.1	2230.3	2410.5	2605.1	2815.3	3041.2	3281.1	3531.2
$R_{F\&M,EOL}$	0.1	0.2	0.5	1.0	2.0	3.6	6.1	10.0	15.6	23.5	34.4	49.1	68.5	93.8	126.0	166.3	216.1	276.3	348.2
$Out_{MP} = In_{FM}$	922.3	2092.4	3121.4	4080.1	4975.2	5814.5	6607.2	7364.2	8097.8	8666.9	9247.4	9853.3	10498.5	11195.8	11956.0	12785.8	13686.5	14652.3	15668.6
$Out_{FM} = In_{Use}$	451.4	1041.3	1578.9	2097.2	2597.9	3083.6	3558.0	4025.7	4492.9	4879.5	5281.8	5708.3	6167.8	6669.0	7219.4	7824.9	8487.9	9206.5	9973.0
$Out_{Use} = In_{EOL}$	0.2	0.4	0.8	1.7	3.2	5.6	9.4	15.2	23.5	35.2	51.4	73.1	101.8	138.8	185.9	244.7	316.9	404.1	507.6
$L_{MP,env}$	16.8	36.8	53.0	66.9	78.7	88.6	96.9	103.8	109.6	112.6	115.0	117.2	119.3	121.3	123.3	125.2	127.0	128.5	129.5
$L_{MP,omf}$	16.8	36.8	53.0	66.9	78.7	88.6	96.9	103.8	109.6	112.6	115.0	117.2	119.3	121.3	123.3	125.2	127.0	128.5	129.5
$L_{MP,lf}$	721.0	1617.3	2385.5	3082.9	3716.6	4294.4	4824.6	5316.4	5779.7	6115.6	6451.0	6795.5	7158.0	7546.5	7966.9	8422.5	8912.7	9432.4	9970.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	294.5	640.9	916.2	1146.6	1337.2	1493.1	1619.1	1720.1	1800.6	1832.2	1855.9	1874.5	1890.3	1904.7	1918.3	1931.0	1941.7	1948.2	1947.9
$Stock_{Use}$	7915.5	8956.4	10534.5	12630.0	15224.7	18302.7	21851.2	25861.8	30331.2	35175.4	40405.8	46041.0	52107.1	58637.2	65670.8	73251.0	81422.0	90224.4	99689.9
$\sum R$	143.7	482.9	1007.9	1717.8	2611.3	3686.7	4943.0	6380.1	7999.9	9775.1	11713.0	13824.2	16123.0	18627.3	21358.4	24340.0	27597.3	31154.7	35034.1
$\sum L_{OMF}$	311.3	989.1	1958.7	3172.8	4589.7	6173.2	7892.2	9720.8	11638.2	13593.5	15579.7	17593.1	19632.7	21699.2	23794.7	25921.4	28080.8	30272.5	32493.3
$\sum L_{LF}$	753.8	2442.3	4929.7	8140.0	12005.3	16465.8	21470.7	26978.7	32959.2	39279.6	45938.5	52944.7	60316.1	68078.8	76264.8	84909.7	94048.3	103709.9	113913.2
$\sum L_{Env}$	16.8	53.6	106.6	173.4	252.1	340.7	437.6	541.4	651.0	763.6	878.6	995.9	1115.2	1236.5	1359.7	1484.9	1611.9	1740.3	1869.8

Table A 43: Results – CIGS PV Cells – Gallium – EOL-II scenarios – No recycling – Min

EOL-II scenarios – No recycling – Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	534.0	67.0	74.6	81.3	87.3	92.8	98.1	103.4	109.1	103.4	98.9	95.3	92.6	90.5	88.8	87.2	85.4	83.2	80.2
$L_{F\&M,LF}$	10.4	1.3	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.4	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.7	0.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.1	0.2	0.4	0.6	1.1	1.7	2.6	3.8	5.4	7.6	10.3	13.8	18.0	23.1	29.1	36.2	44.3
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.4	0.6	0.8	1.1	1.5	2.0	2.6	3.2	4.0	4.9
$R_{F\&M}$	45.7	6.0	7.0	7.9	8.8	9.7	10.5	11.4	12.4	12.1	11.8	11.6	11.5	11.5	11.5	11.4	11.4	11.2	10.9
$R_{F\&M,EOL}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	293.7	37.0	41.5	45.4	49.1	52.4	55.7	59.1	62.7	59.7	57.4	55.6	54.3	53.4	52.6	51.9	51.1	50.1	48.5
$Out_{FM} = In_{Use}$	143.8	18.4	21.0	23.4	25.6	27.8	30.0	32.3	34.8	33.6	32.8	32.2	31.9	31.8	31.8	31.8	31.7	31.5	30.9
$Out_{Use} = In_{EOL}$	0.0	0.1	0.1	0.2	0.4	0.7	1.2	1.9	2.9	4.2	6.1	8.4	11.5	15.3	20.0	25.6	32.4	40.2	49.3
$L_{MP,env}$	5.3	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4
$L_{MP,omf}$	5.3	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4
$L_{MP,lf}$	229.6	28.6	31.7	34.3	36.7	38.7	40.7	42.7	44.7	42.1	40.0	38.4	37.0	36.0	35.1	34.2	33.3	32.2	30.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	93.8	11.3	12.2	12.8	13.2	13.5	13.7	13.8	13.9	12.6	11.5	10.6	9.8	9.1	8.4	7.8	7.3	6.7	6.0
$Stock_{Use}$	2618.6	2637.0	2657.9	2681.0	2706.2	2733.3	2762.2	2792.6	2824.5	2853.9	2880.6	2904.4	2924.8	2941.3	2953.2	2959.3	2958.6	2949.9	2931.5
$\sum R$	45.7	51.7	58.7	66.6	75.4	85.1	95.6	107.1	119.5	131.5	143.4	155.0	166.5	178.0	189.5	200.9	212.3	223.5	234.4
$\sum L_{OMF}$	99.2	111.2	124.2	137.9	152.2	167.1	182.6	199.0	216.3	233.5	251.2	270.0	290.8	314.2	341.1	372.6	409.4	452.7	503.5
$\sum L_{LF}$	240.1	270.0	303.0	338.8	377.0	417.3	459.6	504.0	550.5	594.5	636.4	676.8	716.1	754.6	792.6	830.2	867.6	904.6	941.0
$\sum L_{Env}$	5.3	6.0	6.7	7.4	8.2	9.0	9.8	10.7	11.5	12.3	13.0	13.7	14.3	14.9	15.4	15.9	16.4	16.8	17.2

Table A 44: Results – CIGS PV Cells – Gallium – EOL-II scenarios – No recycling – Max

EOL-II scenarios – No recycling – Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1676.8	3783.3	5612.9	7296.7	8849.1	10286.0	11625.5	12888.2	14096.8	15007.6	15928.5	16883.3	17895.1	18984.9	20169.4	21458.7	22853.2	24341.6	25898.5
$L_{F\&M,LF}$	32.7	71.2	101.8	127.4	148.6	165.9	179.9	191.1	200.1	203.6	206.2	208.3	210.0	211.6	213.1	214.6	215.7	216.5	216.4
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.2	0.4	0.8	1.5	2.8	5.0	8.5	13.7	21.1	31.7	46.3	65.8	91.6	124.9	167.3	220.2	285.2	363.7	456.8
$L_{EOL,lf}$	0.0	0.0	0.1	0.2	0.3	0.6	0.9	1.5	2.3	3.5	5.1	7.3	10.2	13.9	18.6	24.5	31.7	40.4	50.8
$R_{F\&M}$	143.6	339.0	524.4	708.9	891.5	1071.9	1250.2	1427.2	1604.2	1751.7	1903.5	2062.1	2230.3	2410.5	2605.1	2815.3	3041.2	3281.1	3531.2
$R_{F\&M,EOL}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	922.3	2092.4	3121.4	4080.1	4975.2	5814.5	6607.2	7364.2	8097.8	8666.9	9247.4	9853.3	10498.5	11195.8	11956.0	12785.8	13686.5	14652.3	15668.6
$Out_{FM} = In_{Use}$	451.4	1041.3	1578.9	2097.2	2597.9	3083.6	3558.0	4025.7	4492.9	4879.5	5281.8	5708.3	6167.8	6669.0	7219.4	7824.9	8487.9	9206.5	9973.0
$Out_{Use} = In_{EOL}$	0.2	0.4	0.8	1.7	3.2	5.6	9.4	15.2	23.5	35.2	51.4	73.1	101.8	138.8	185.9	244.7	316.9	404.1	507.6
$L_{MP,env}$	16.8	36.8	53.0	66.9	78.7	88.6	96.9	103.8	109.6	112.6	115.0	117.2	119.3	121.3	123.3	125.2	127.0	128.5	129.5
$L_{MP,omf}$	16.8	36.8	53.0	66.9	78.7	88.6	96.9	103.8	109.6	112.6	115.0	117.2	119.3	121.3	123.3	125.2	127.0	128.5	129.5
$L_{MP,lf}$	721.0	1617.3	2385.5	3082.9	3716.6	4294.4	4824.6	5316.4	5779.7	6115.6	6451.0	6795.5	7158.0	7546.5	7966.9	8422.5	8912.7	9432.4	9970.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	294.5	640.9	916.2	1146.6	1337.2	1493.1	1619.1	1720.1	1800.6	1832.2	1855.9	1874.5	1890.3	1904.7	1918.3	1931.0	1941.7	1948.2	1947.9
$Stock_{Use}$	7915.5	8956.4	10534.5	12630.0	15224.7	18302.7	21851.2	25861.8	30331.2	35175.4	40405.8	46041.0	52107.1	58637.2	65670.8	73251.0	81422.0	90224.4	99689.9
$\sum R$	143.6	482.6	1007.0	1715.9	2607.4	3679.3	4929.4	6356.6	7960.8	9712.5	11615.9	13678.1	15908.3	18318.9	20924.0	23739.3	26780.5	30061.5	33592.7
$\sum L_{OMF}$	311.4	989.4	1959.4	3174.5	4593.2	6179.9	7904.4	9742.0	11673.4	13649.9	15667.1	17724.7	19825.9	21976.8	24185.7	26462.1	28816.0	31256.3	33790.5
$\sum L_{LF}$	753.8	2442.4	4929.7	8140.2	12005.7	16466.6	21472.0	26981.0	32963.2	39285.8	45948.2	52959.3	60337.6	68109.6	76308.3	84969.8	94130.0	103819.2	114057.3
$\sum L_{Env}$	16.8	53.6	106.6	173.4	252.1	340.7	437.6	541.4	651.0	763.6	878.6	995.9	1115.2	1236.5	1359.7	1484.9	1611.9	1740.3	1869.8

Table A 45: Results – CIGS PV Cells – Gallium – EOL-II scenarios – High efficiency recycling – Min

EOL-II scenarios – High efficiency recycling – Min – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	534.0	67.0	74.6	81.3	87.3	92.8	98.1	103.4	109.1	103.4	98.9	95.3	92.6	90.5	88.8	87.2	85.4	83.2	80.2
$L_{F\&M,LF}$	10.4	1.3	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.4	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.7	0.7
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.5	0.7	0.9	1.2	1.6	2.0	2.4	2.9	3.4	3.9	4.3
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5
$R_{F\&M}$	45.7	6.0	7.0	7.9	8.8	9.7	10.5	11.4	12.4	12.1	11.8	11.6	11.5	11.5	11.5	11.4	11.4	11.2	10.9
$R_{F\&M,EOL}$	0.0	0.0	0.1	0.2	0.3	0.6	0.9	1.5	2.3	3.5	5.0	7.0	9.7	13.1	17.3	22.4	28.6	35.9	44.5
$Out_{MP} = In_{FM}$	293.7	37.0	41.5	45.4	49.1	52.4	55.7	59.1	62.7	59.7	57.4	55.6	54.3	53.4	52.6	51.9	51.1	50.1	48.5
$Out_{FM} = In_{Use}$	143.8	18.4	21.0	23.4	25.6	27.8	30.0	32.3	34.8	33.6	32.8	32.2	31.9	31.8	31.8	31.8	31.7	31.5	30.9
$Out_{Use} = In_{EOL}$	0.0	0.1	0.1	0.2	0.4	0.7	1.2	1.9	2.9	4.2	6.1	8.4	11.5	15.3	20.0	25.6	32.4	40.2	49.3
$L_{MP,env}$	5.3	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4
$L_{MP,omf}$	5.3	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4
$L_{MP,lf}$	229.6	28.6	31.7	34.3	36.7	38.7	40.7	42.7	44.7	42.1	40.0	38.4	37.0	36.0	35.1	34.2	33.3	32.2	30.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	93.8	11.3	12.2	12.8	13.2	13.5	13.7	13.8	13.9	12.6	11.5	10.6	9.8	9.1	8.4	7.8	7.3	6.7	6.0
$Stock_{Use}$	2618.6	2637.0	2657.9	2681.0	2706.2	2733.3	2762.2	2792.6	2824.5	2853.9	2880.6	2904.4	2924.8	2941.3	2953.2	2959.3	2958.6	2949.9	2931.5
$\sum R$	45.8	51.8	58.8	66.9	76.0	86.2	97.7	110.7	125.4	140.9	157.7	176.4	197.7	222.2	251.0	284.8	324.8	371.9	427.3
$\sum L_{OMF}$	99.1	111.1	124.0	137.6	151.6	166.0	180.7	195.7	211.0	225.1	238.3	250.7	262.7	274.4	285.8	297.1	308.2	319.2	329.9
$\sum L_{LF}$	240.1	270.0	303.0	338.8	376.9	417.1	459.4	503.6	549.9	593.5	635.0	674.6	712.9	750.1	786.4	821.8	856.3	889.7	921.7
$\sum L_{Env}$	5.3	6.0	6.7	7.4	8.2	9.0	9.8	10.7	11.5	12.3	13.0	13.7	14.3	14.9	15.4	15.9	16.4	16.8	17.2

Table A 46: Results – CIGS PV Cells – Gallium – EOL-II scenarios – High efficiency recycling – Max

EOL-II scenarios – High efficiency recycling – Max – Stocks and Flows in kilograms																			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	1676.8	3783.3	5612.9	7296.7	8849.1	10286.0	11625.5	12888.2	14096.8	15007.6	15928.5	16883.3	17895.1	18984.9	20169.4	21458.7	22853.2	24341.6	25898.5
$L_{F\&M,LF}$	32.7	71.2	101.8	127.4	148.6	165.9	179.9	191.1	200.1	203.6	206.2	208.3	210.0	211.6	213.1	214.6	215.7	216.5	216.4
$L_{Use,Env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,omf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{Use,lf}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,omf}$	0.0	0.1	0.2	0.3	0.6	1.1	1.7	2.7	4.1	5.8	8.0	10.8	14.2	18.1	22.7	27.8	33.2	38.9	44.5
$L_{EOL,lf}$	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.5	0.6	0.9	1.2	1.6	2.0	2.5	3.1	3.7	4.3	4.9
$R_{F\&M}$	143.6	339.0	524.4	708.9	891.5	1071.9	1250.2	1427.2	1604.2	1751.7	1903.5	2062.1	2230.3	2410.5	2605.1	2815.3	3041.2	3281.1	3531.2
$R_{F\&M,EOL}$	0.1	0.3	0.6	1.3	2.5	4.4	7.5	12.2	19.0	28.8	42.5	61.1	86.0	118.7	160.7	213.9	280.0	360.8	458.1
$Out_{MP} = In_{FM}$	922.3	2092.4	3121.4	4080.1	4975.2	5814.5	6607.2	7364.2	8097.8	8666.9	9247.4	9853.3	10498.5	11195.8	11956.0	12785.8	13686.5	14652.3	15668.6
$Out_{FM} = In_{Use}$	451.4	1041.3	1578.9	2097.2	2597.9	3083.6	3558.0	4025.7	4492.9	4879.5	5281.8	5708.3	6167.8	6669.0	7219.4	7824.9	8487.9	9206.5	9973.0
$Out_{Use} = In_{EOL}$	0.2	0.4	0.8	1.7	3.2	5.6	9.4	15.2	23.5	35.2	51.4	73.1	101.8	138.8	185.9	244.7	316.9	404.1	507.6
$L_{MP,env}$	16.8	36.8	53.0	66.9	78.7	88.6	96.9	103.8	109.6	112.6	115.0	117.2	119.3	121.3	123.3	125.2	127.0	128.5	129.5
$L_{MP,omf}$	16.8	36.8	53.0	66.9	78.7	88.6	96.9	103.8	109.6	112.6	115.0	117.2	119.3	121.3	123.3	125.2	127.0	128.5	129.5
$L_{MP,lf}$	721.0	1617.3	2385.5	3082.9	3716.6	4294.4	4824.6	5316.4	5779.7	6115.6	6451.0	6795.5	7158.0	7546.5	7966.9	8422.5	8912.7	9432.4	9970.9
$L_{F\&M,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{F\&M,omf}$	294.5	640.9	916.2	1146.6	1337.2	1493.1	1619.1	1720.1	1800.6	1832.2	1855.9	1874.5	1890.3	1904.7	1918.3	1931.0	1941.7	1948.2	1947.9
$Stock_{Use}$	7915.5	8956.4	10534.5	12630.0	15224.7	18302.7	21851.2	25861.8	30331.2	35175.4	40405.8	46041.0	52107.1	58637.2	65670.8	73251.0	81422.0	90224.4	99689.9
$\sum R$	143.7	483.0	1008.1	1718.3	2612.3	3688.5	4946.2	6385.6	8008.7	9789.2	11735.1	13858.4	16174.7	18703.9	21469.8	24499.0	27820.1	31462.0	35451.3
$\sum L_{OMF}$	311.3	989.0	1958.5	3172.3	4588.8	6171.6	7889.3	9716.0	11630.3	13580.8	15559.8	17562.4	19586.1	21630.2	23694.5	25778.4	27880.3	29995.9	32117.8
$\sum L_{LF}$	753.8	2442.3	4929.6	8139.9	12005.2	16465.7	21470.4	26978.2	32958.4	39278.2	45936.3	52941.3	60311.0	68071.1	76253.7	84893.9	94026.0	103679.2	113871.5
$\sum L_{Env}$	16.8	53.6	106.6	173.4	252.1	340.7	437.6	541.4	651.0	763.6	878.6	995.9	1115.2	1236.5	1359.7	1484.9	1611.9	1740.3	1869.8

Appendix B) Polymerization catalysts

Data

Table A 47: Beverage amounts for different PET packaging types [in Mio. liters]

	Beer and shandy		Water		Soft drinks	
Year	**One-way**	**Refillable**	**One-way**	**Refillable**	**One-way**	**Refillable**
2012	508 (457-558)	-	7,977 (7,180-8,775)	2,454 (2,208-2,699)	7,368 (6,631-8,105)	2,321 (2,089-2,554)
2013	508 (458-559)	-	8,099 (7,290-8,909)	2,430 (2,187-2,673)	7,449 (6,704-8,194)	2,291 (2,062-2,520)
2014	509 (458-560)	-	8,222 (7,399-9,044)	2,407 (2,166-2,648)	7,531 (6,777-8,284)	2,260 (2,034-2,486)
2015	510 (459-561)	-	8,344 (7,509-9,178)	2,384 (2,146-2,622)	7,612 (6,851-8,373)	2,229 (2,006-2,452)
2016	511 (459-562)	-	8,466 (7,619-9,312)	2,361 (2,125-2,597)	7,693 (6,924-8,462)	2,198 (1,978-2,418)
2017	511 (460-562)	-	8,588 (7,729-9,447)	2,337 (2,104-2,571)	7,774 (6,997-8,552)	2,167 (1,950-2,384)
2018	512 (461-563)	-	8,710 (7,839-9,581)	2,314 (2,083-2,546)	7,856 (7,070-8,641)	2,136 (1,923-2,350)
2019	513 (461-564)	-	8,832 (7,949-9,715)	2,291 (2,062-2,520)	7,937 (7,143-8,731)	2,106 (1,895-2,316)
2020	513 (462-565)	-	8,954 (8,059-9,850)	2,268 (2,041-2,494)	8,018 (7,217-8,820)	2,075 (1,867-2,282)
2021	514 (463-565)	-	9,076 (8,169-9,984)	2,244 (2,020-2,469)	8,100 (7,290-8,910)	2,044 (1,839-2,248)
2022	515 (463-566)	-	9,198 (8,279-10,118)	2,221 (1,999-2,443)	8,181 (7,363-8,999)	2,013 (1,812-2,214)
2023	515 (464-567)	-	9,321 (8,388-10,253)	2,198 (1,978-2,418)	8,262 (7,436-9,088)	1,982 (1,784-2,180)
2024	516 (465-568)	-	9,443 (8,498-10,387)	2,175 (1,957-2,392)	8,344 (7,509-9,178)	1,951 (1,756-2,146)
2025	517 (465-569)	-	9,565 (8,608-10,521)	2,151 (1,936-2,366)	8,425 (7,582-9,267)	1,920 (1,728-2,113)
2026	518 (466-569)	-	9,687 (8,718-10,656)	2,128 (1,915-2,341)	8,506 (7,656-9,357)	1,890 (1,701-2,079)
2027	518 (466-570)	-	9,809 (8,828-10,790)	2,105 (1,894-2,315)	8,587 (7,729-9,446)	1,859 (1,673-2,045)
2028	519 (467-571)	-	9,931 (8,938-10,924)	2,082 (1,873-2,290)	8,669 (7,802-9,536)	1,828 (1,645-2,011)
2029	520 (468-572)	-	10,053 (9,048-11,058)	2,058 (1,852-2,264)	8,750 (7,875-9,625)	1,797 (1,617-1,977)
2030	520 (468-572)	-	10,175 (9,158-11,193)	2,035 (1,832-2,239)	8,831 (7,948-9,715)	1,766 (1,590-1,943)

Results

In the following, the full results for all analyzed scenarios are presented. The parameters are explicated in the following table.

Table A 48: Abbreviations and notations of stocks and flows used in polymerization catalyst case study

Flow	Parameter
Input flows in material production (environment to technosphere)	In_{MP}
Dissipative losses from EOL to landfills	$L_{EOL,lf}$
Bottle-to-bottle recycling flow	R_{B2B}
Dissipative losses from material production to other material flows	$L_{MP,OMF}$
Dissipative losses from material production to environment	$L_{MP,Env}$
Dissipative losses from F&M to landfills	$L_{F\&M,LF}$
Input flow to F&M / material demand	$Out_{MP} = In_{FM}$
Input flow to use phase	$Out_{FM} = In_{Use}$
Dissipation to other material flows=PET	$L_{Use,OMF} = In_{FM-PET}$
Input flow to PET use phase (polymerization process)	$Out_{FM-PET} = In_{Use-PET}$
Input flows to PET-EOL phase	$Out_{Use-PET} = In_{EOL-PET}$
Dissipative losses from material production to landfills	$L_{MP,lf}$
Dissipative losses from use phase of PET bottles to environment	$L_{Use-PET,env}$
Dissipative losses from end-of-life of PET bottles to other material flows	$L_{EOL,OMF}$
In-Use stock	$Stock_{Use}$
Cumulative dissipative losses to environment (cumulative, starting from 2012)	$\sum L_{Env}$
Cumulative dissipative losses to other material flows (cumulative, starting from 2012)	$\sum L_{OMF}$
Cumulative dissipative losses to landfills (cumulative, starting from 2012)	$\sum L_{LF}$

Table A 49: Results - Polymerization catalysts - Baseline-Scenario - Min

Baseline-Scenario – Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	276.0	278.3	280.6	283.0	285.2	287.5	289.8	292.0	294.3	296.5	298.7	300.9	303.1	305.2	307.4	309.5	311.6	313.7	315.8
$L_{EOL,lf}$	17.3	17.6	17.8	18.0	18.2	18.4	18.6	18.8	19.0	19.2	19.4	19.6	19.8	20.0	20.2	20.4	20.6	20.8	21.0
R_{B2B}	302.7	306.3	309.8	313.4	316.9	320.5	324.1	327.6	331.2	334.7	338.3	341.9	345.4	349.0	352.5	356.1	359.6	363.2	366.8
$L_{MP,OMF}$	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1
$L_{MP,Env}$	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	234.6	237.4	240.1	242.9	245.6	248.4	251.1	253.9	256.7	259.4	262.2	264.9	267.7	270.5	273.2	276.0	278.7	281.5	284.2
$Out_{FM} = In_{Use}$	234.6	237.4	240.1	242.9	245.6	248.4	251.1	253.9	256.7	259.4	262.2	264.9	267.7	270.5	273.2	276.0	278.7	281.5	284.2
$L_{Use,OMF} = In_{F\&M-PET}$	234.6	237.4	240.1	242.9	245.6	248.4	251.1	253.9	256.7	259.4	262.2	264.9	267.7	270.5	273.2	276.0	278.7	281.5	284.2
$Out_{F\&M-PET} = In_{Use-PET}$	537.3	543.6	549.9	556.2	562.6	568.9	575.2	581.5	587.8	594.2	600.5	606.8	613.1	619.4	625.7	632.1	638.4	644.7	651.0
$Out_{Use-PET} = In_{EOL-PET}$	536.7	543.0	549.3	555.6	561.9	568.3	574.6	580.9	587.2	593.5	599.8	606.1	612.4	618.7	625.1	631.4	637.7	644.0	650.3
$L_{MP,env}$	38.6	38.3	37.8	37.4	37.0	36.5	36.0	35.6	35.1	34.6	34.1	33.5	33.0	32.5	31.9	31.3	30.7	30.1	29.5
$L_{Use-PET,env}$	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
$L_{EOL,OMF}$	216.7	219.2	221.8	224.3	226.8	229.4	231.9	234.5	237.0	239.6	242.1	244.7	247.2	249.8	252.3	254.9	257.4	260.0	262.5
$Stock_{Use}$	536.7	543.0	549.3	555.6	562.0	568.3	574.6	580.9	587.2	593.5	599.8	606.1	612.4	618.7	625.1	631.4	637.7	644.0	650.3
$\sum L_{Env}$	2.0	3.9	5.9	7.8	9.8	11.7	13.5	15.4	17.3	19.2	21.1	23.0	24.9	26.8	28.6	30.4	32.2	34.0	35.7
$\sum L_{OMF}$	218.1	438.6	661.8	887.4	1115.6	1346.3	1579.4	1815.2	2053.5	2294.3	2537.6	2783.5	3031.9	3282.9	3536.3	3792.3	4050.8	4311.9	4575.4
$\sum L_{LF}$	55.9	111.8	167.4	222.8	278.0	332.9	387.5	441.9	496.0	549.8	603.3	656.4	709.2	761.7	813.8	865.5	916.8	967.6	1018.1

Table A 50: Results - Polymerization catalysts - Baseline-Scenario - Max

Baseline-Scenario - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	831.8	841.7	851.5	861.4	871.2	881.0	890.9	900.7	910.5	920.3	930.2	940.0	949.8	959.6	969.4	979.3	989.1	998.9	1008.7
$L_{EOL,lf}$	52.3	53.1	53.9	54.7	55.5	56.3	57.1	57.9	58.7	59.5	60.4	61.2	62.0	62.9	63.7	64.6	65.4	66.3	67.1
R_{B2B}	912.3	926.1	940.0	954.0	968.0	982.1	996.2	1010.4	1024.7	1039.1	1053.5	1068.0	1082.6	1097.2	1111.9	1126.7	1141.5	1156.4	1171.4
$L_{MP,OMF}$	4.2	4.1	4.1	4.1	4.0	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4
$L_{MP,Env}$	4.2	4.1	4.1	4.1	4.0	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	707.1	717.8	728.5	739.3	750.2	761.1	772.1	783.1	794.2	805.3	816.5	827.7	839.0	850.3	861.7	873.2	884.7	896.2	907.8
$Out_{FM} = In_{Use}$	707.1	717.8	728.5	739.3	750.2	761.1	772.1	783.1	794.2	805.3	816.5	827.7	839.0	850.3	861.7	873.2	884.7	896.2	907.8
$L_{Use,OMF} = In_{F\&M-PET}$	707.1	717.8	728.5	739.3	750.2	761.1	772.1	783.1	794.2	805.3	816.5	827.7	839.0	850.3	861.7	873.2	884.7	896.2	907.8
$Out_{F\&M-PET} = In_{Use-PET}$	1619.4	1643.9	1668.5	1693.3	1718.2	1743.2	1768.3	1793.5	1818.9	1844.4	1870.0	1895.7	1921.6	1947.5	1973.6	1999.8	2026.2	2052.6	2079.2
$Out_{Use-PET} = In_{EOL-PET}$	1617.6	1642.1	1666.7	1691.4	1716.3	1741.3	1766.4	1791.6	1816.9	1842.4	1867.9	1893.6	1919.5	1945.4	1971.5	1997.6	2023.9	2050.4	2076.9
$L_{MP,env}$	116.5	115.6	114.8	113.9	112.9	111.9	110.9	109.8	108.5	107.3	106.1	104.8	103.4	102.0	100.5	99.0	97.4	95.9	94.2
$L_{Use-PET,env}$	1.8	1.8	1.8	1.9	1.9	1.9	1.9	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.2	2.2	2.2	2.3	2.3
$L_{EOL,OMF}$	653.0	662.9	672.8	682.8	692.8	702.9	713.0	723.2	733.5	743.7	754.1	764.4	774.9	785.3	795.8	806.4	817.0	827.7	838.4
$Stock_{Use}$	1617.6	1642.1	1666.7	1691.4	1716.3	1741.3	1766.4	1791.6	1816.9	1842.4	1868.0	1893.7	1919.5	1945.4	1971.5	1997.7	2024.0	2050.4	2076.9
$\sum L_{Env}$	6.0	11.9	17.8	23.8	29.7	35.6	41.4	47.4	53.2	59.1	65.0	70.8	76.6	82.3	88.1	93.9	99.6	105.3	110.9
$\sum L_{OMF}$	657.2	1324.2	2001.1	2688.0	3384.8	4091.7	4808.6	5535.8	6273.1	7020.7	7778.6	8546.7	9325.3	10114.2	10913.6	11723.6	12544.1	13375.2	14216.9
$\sum L_{LF}$	168.8	337.5	506.2	674.8	843.2	1011.4	1179.4	1347.1	1514.3	1681.1	1847.7	2013.7	2179.1	2344.0	2508.2	2671.9	2834.7	2996.8	3158.1

Table A 51: Results - Polymerization catalysts - MP alternative Scenario B - Min

Material production alternative (Scenario B) - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	2345.9	2373.5	2401.1	2428.7	2456.3	2483.9	2511.4	2539.0	2566.6	2594.2	2621.8	2649.4	2677.0	2704.5	2732.1	2759.7	2787.3	2814.9	2842.5
$L_{EOL,lf}$	17.3	17.6	17.8	18.0	18.2	18.4	18.6	18.8	19.0	19.2	19.4	19.6	19.8	20.0	20.2	20.4	20.6	20.8	21.0
R_{B2B}	302.7	306.3	309.8	313.4	316.9	320.5	324.1	327.6	331.2	334.7	338.3	341.9	345.4	349.0	352.5	356.1	359.6	363.2	366.8
$L_{MP,OMF}$	23.5	23.7	24.0	24.3	24.6	24.8	25.1	25.4	25.7	25.9	26.2	26.5	26.8	27.0	27.3	27.6	27.9	28.1	28.4
$L_{MP,Env}$	23.5	23.7	24.0	24.3	24.6	24.8	25.1	25.4	25.7	25.9	26.2	26.5	26.8	27.0	27.3	27.6	27.9	28.1	28.4
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	234.6	237.4	240.1	242.9	245.6	248.4	251.1	253.9	256.7	259.4	262.2	264.9	267.7	270.5	273.2	276.0	278.7	281.5	284.2
$Out_{FM} = In_{Use}$	234.6	237.4	240.1	242.9	245.6	248.4	251.1	253.9	256.7	259.4	262.2	264.9	267.7	270.5	273.2	276.0	278.7	281.5	284.2
$L_{Use,OMF} = In_{F\&M-PET}$	234.6	237.4	240.1	242.9	245.6	248.4	251.1	253.9	256.7	259.4	262.2	264.9	267.7	270.5	273.2	276.0	278.7	281.5	284.2
$Out_{F\&M-PET} = In_{Use-PET}$	537.3	543.6	549.9	556.2	562.6	568.9	575.2	581.5	587.8	594.2	600.5	606.8	613.1	619.4	625.7	632.1	638.4	644.7	651.0
$Out_{Use-PET} = In_{EOL-PET}$	536.7	543.0	549.3	555.6	561.9	568.3	574.6	580.9	587.2	593.5	599.8	606.1	612.4	618.7	625.1	631.4	637.7	644.0	650.3
$L_{MP,env}$	2064.4	2088.7	2113.0	2137.2	2161.5	2185.8	2210.1	2234.3	2258.7	2282.9	2307.2	2331.4	2355.8	2380.0	2404.3	2428.5	2452.9	2477.1	2501.4
$L_{Use-PET,env}$	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
$L_{EOL,OMF}$	216.7	219.2	221.8	224.3	226.8	229.4	231.9	234.5	237.0	239.6	242.1	244.7	247.2	249.8	252.3	254.9	257.4	260.0	262.5
$Stock_{Use}$	536.7	543.0	549.3	555.6	561.9	568.3	574.6	580.9	587.2	593.5	599.8	606.1	612.4	618.7	625.1	631.4	637.7	644.0	650.3
$\sum L_{Env}$	24.0	48.4	73.0	97.9	123.0	148.5	174.2	200.2	226.5	253.1	280.0	307.2	334.7	362.4	390.4	418.7	447.3	476.2	505.3
$\sum L_{OMF}$	240.2	483.1	728.9	977.5	1228.9	1483.1	1740.1	2000.0	2262.7	2528.2	2796.5	3067.7	3341.7	3618.5	3898.2	4180.7	4465.9	4754.1	5045.0
$\sum L_{LF}$	2081.7	4188.0	6318.8	8474.0	10653.7	12857.9	15086.6	17339.7	19617.4	21919.5	24246.1	26597.1	28972.6	31372.6	33797.1	36246.0	38719.5	41217.4	43739.7

Table A 52: Results - Polymerization catalysts - MP alternative Scenario B - Max

Material production alternative (Scenario B) - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	7070.5	7177.6	7285.2	7393.3	7501.9	7611.1	7720.8	7831.0	7941.7	8053.0	8164.8	8277.2	8390.0	8503.4	8617.3	8731.7	8846.7	8962.2	9078.2
$L_{EOL,lf}$	52.3	53.1	53.9	54.7	55.5	56.3	57.1	57.9	58.7	59.5	60.4	61.2	62.0	62.9	63.7	64.6	65.4	66.3	67.1
R_{B2B}	912.3	926.1	940.0	954.0	968.0	982.1	996.2	1010.4	1024.7	1039.1	1053.5	1068.0	1082.6	1097.2	1111.9	1126.7	1141.5	1156.4	1171.4
$L_{MP,OMF}$	70.7	71.8	72.9	73.9	75.0	76.1	77.2	78.3	79.4	80.5	81.6	82.8	83.9	85.0	86.2	87.3	88.5	89.6	90.8
$L_{MP,Env}$	70.7	71.8	72.9	73.9	75.0	76.1	77.2	78.3	79.4	80.5	81.6	82.8	83.9	85.0	86.2	87.3	88.5	89.6	90.8
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	707.1	717.8	728.5	739.3	750.2	761.1	772.1	783.1	794.2	805.3	816.5	827.7	839.0	850.3	861.7	873.2	884.7	896.2	907.8
$Out_{FM} = In_{Use}$	707.1	717.8	728.5	739.3	750.2	761.1	772.1	783.1	794.2	805.3	816.5	827.7	839.0	850.3	861.7	873.2	884.7	896.2	907.8
$L_{Use,OMF} = In_{F\&M-PET}$	707.1	717.8	728.5	739.3	750.2	761.1	772.1	783.1	794.2	805.3	816.5	827.7	839.0	850.3	861.7	873.2	884.7	896.2	907.8
$Out_{F\&M-PET} = In_{Use-PET}$	1619.4	1643.9	1668.5	1693.3	1718.2	1743.2	1768.3	1793.5	1818.9	1844.4	1870.0	1895.7	1921.6	1947.5	1973.6	1999.8	2026.2	2052.6	2079.2
$Out_{Use-PET} = In_{EOL-PET}$	1617.6	1642.1	1666.7	1691.4	1716.3	1741.3	1766.4	1791.6	1816.9	1842.4	1867.9	1893.6	1919.5	1945.4	1971.5	1997.6	2023.9	2050.4	2076.9
$L_{MP,env}$	6222.1	6316.2	6410.9	6506.0	6601.7	6697.8	6794.3	6891.3	6988.8	7086.6	7185.0	7283.9	7383.2	7483.0	7583.3	7684.0	7785.1	7886.8	7988.8
$L_{Use-PET,env}$	1.8	1.8	1.8	1.9	1.9	1.9	1.9	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.2	2.2	2.2	2.3	2.3
$L_{EOL,OMF}$	653.0	662.9	672.8	682.8	692.8	702.9	713.0	723.2	733.5	743.7	754.1	764.4	774.9	785.3	795.8	806.4	817.0	827.7	838.4
$Stock_{Use}$	1617.6	1642.1	1666.7	1691.4	1716.3	1741.3	1766.4	1791.6	1816.9	1842.4	1868.0	1893.7	1919.5	1945.4	1971.5	1997.7	2024.0	2050.4	2076.9
$\sum L_{Env}$	72.5	146.1	220.7	296.6	373.5	451.5	530.6	610.9	692.3	774.9	858.6	943.5	1029.5	1116.6	1205.0	1294.5	1385.2	1477.1	1570.2
$\sum L_{OMF}$	723.7	1458.4	2204.0	2960.8	3728.6	4507.6	5297.8	6099.3	6912.2	7736.5	8572.2	9419.4	10278.2	11148.5	12030.5	12924.2	13829.7	14747.0	15676.2
$\sum L_{LF}$	6274.4	12643.7	19108.5	25669.3	32326.4	39080.5	45931.9	52881.1	59928.5	67074.7	74320.1	81665.1	89110.3	96656.3	104303.2	112051.8	119902.3	127855.3	135911.2

Table A 53: Results - Polymerization catalysts - In-use dissipation min - Min

In-use dissipation min - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	275.6	277.9	280.2	282.6	284.8	287.1	289.4	291.6	293.8	296.1	298.3	300.4	302.6	304.8	306.9	309.1	311.2	313.3	315.4
$L_{EOL,lf}$	17.4	17.6	17.8	18.0	18.2	18.4	18.6	18.8	19.0	19.2	19.4	19.6	19.8	20.0	20.2	20.4	20.6	20.8	21.0
R_{B2B}	303.0	306.6	310.2	313.7	317.3	320.8	324.4	328.0	331.5	335.1	338.7	342.2	345.8	349.4	352.9	356.5	360.0	363.6	367.2
$L_{MP,OMF}$	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1
$L_{MP,Env}$	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	234.3	237.0	239.8	242.5	245.3	248.0	250.8	253.5	256.3	259.1	261.8	264.6	267.3	270.1	272.8	275.6	278.3	281.1	283.8
$Out_{FM} = In_{Use}$	234.3	237.0	239.8	242.5	245.3	248.0	250.8	253.5	256.3	259.1	261.8	264.6	267.3	270.1	272.8	275.6	278.3	281.1	283.8
$L_{Use,OMF} = In_{F\&M-PET}$	234.3	237.0	239.8	242.5	245.3	248.0	250.8	253.5	256.3	259.1	261.8	264.6	267.3	270.1	272.8	275.6	278.3	281.1	283.8
$Out_{F\&M-PET} = In_{Use-PET}$	537.3	543.6	549.9	556.2	562.6	568.9	575.2	581.5	587.8	594.2	600.5	606.8	613.1	619.4	625.7	632.1	638.4	644.7	651.0
$Out_{Use-PET} = In_{EOL-PET}$	537.3	543.6	549.9	556.2	562.6	568.9	575.2	581.5	587.8	594.2	600.5	606.8	613.1	619.4	625.7	632.1	638.4	644.7	651.0
$L_{MP,env}$	38.5	38.2	37.8	37.3	37.0	36.5	36.0	35.6	35.0	34.5	34.1	33.5	32.9	32.4	31.8	31.3	30.6	30.1	29.4
$L_{Use-PET,env}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{EOL,OMF}$	216.9	219.4	222.0	224.5	227.1	229.6	232.2	234.7	237.3	239.8	242.4	244.9	247.5	250.0	252.6	255.2	257.7	260.3	262.8
$Stock_{Use}$	537.3	543.6	549.9	556.3	562.6	568.9	575.2	581.5	587.8	594.2	600.5	606.8	613.1	619.4	625.7	632.1	638.4	644.7	651.0
$\sum L_{Env}$	1.4	2.7	4.1	5.4	6.7	8.0	9.3	10.6	11.9	13.1	14.3	15.5	16.7	17.8	19.0	20.1	21.2	22.3	23.3
$\sum L_{OMF}$	218.3	439.0	662.4	888.2	1116.6	1347.5	1581.0	1817.0	2055.6	2296.6	2540.2	2786.3	3035.0	3286.1	3539.9	3796.2	4055.0	4316.4	4580.2
$\sum L_{LF}$	55.9	111.7	167.3	222.7	277.8	332.7	387.3	441.7	495.7	549.4	602.9	656.0	708.7	761.1	813.2	864.8	916.0	966.9	1017.3

Table A 54: Results - Polymerization catalysts - In-use dissipation min - Max

In-use dissipation min - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	830.6	842.9	852.7	862.6	872.4	882.3	892.1	902.0	911.8	921.7	931.5	941.3	951.2	961.0	970.8	980.7	990.5	1000.3	1010.1
$L_{EOL,lf}$	52.3	53.0	53.8	54.6	55.4	56.2	57.0	57.8	58.7	59.5	60.3	61.1	62.0	62.8	63.6	64.5	65.3	66.2	67.1
R_{B2B}	913.3	925.1	939.0	952.9	966.9	981.0	995.1	1009.3	1023.6	1038.0	1052.4	1066.8	1081.4	1096.0	1110.7	1125.4	1140.2	1155.1	1170.1
$L_{MP,OMF}$	4.2	4.1	4.1	4.1	4.0	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4
$L_{MP,Env}$	4.2	4.1	4.1	4.1	4.0	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	706.0	718.8	729.6	740.4	751.3	762.2	773.2	784.2	795.3	806.4	817.6	828.9	840.2	851.5	863.0	874.4	885.9	897.5	909.1
$Out_{FM} = In_{Use}$	706.0	718.8	729.6	740.4	751.3	762.2	773.2	784.2	795.3	806.4	817.6	828.9	840.2	851.5	863.0	874.4	885.9	897.5	909.1
$L_{Use,OMF} = In_{F\&M-PET}$	706.0	718.8	729.6	740.4	751.3	762.2	773.2	784.2	795.3	806.4	817.6	828.9	840.2	851.5	863.0	874.4	885.9	897.5	909.1
$Out_{F\&M-PET} = In_{Use-PET}$	1619.4	1643.9	1668.5	1693.3	1718.2	1743.2	1768.3	1793.5	1818.9	1844.4	1870.0	1895.7	1921.6	1947.5	1973.6	1999.8	2026.2	2052.6	2079.2
$Out_{Use-PET} = In_{EOL-PET}$	1619.4	1640.3	1664.9	1689.6	1714.4	1739.3	1764.4	1789.6	1814.9	1840.3	1865.9	1891.6	1917.4	1943.3	1969.3	1995.4	2021.7	2048.1	2074.6
$L_{MP,env}$	116.3	115.8	115.0	114.1	113.1	112.1	111.0	109.9	108.7	107.5	106.2	104.9	103.6	102.1	100.7	99.1	97.6	95.9	94.3
$L_{Use-PET,env}$	0.0	3.6	3.7	3.7	3.8	3.8	3.9	3.9	4.0	4.1	4.1	4.2	4.2	4.3	4.3	4.4	4.5	4.5	4.6
$L_{EOL,OMF}$	653.7	662.1	672.1	682.0	692.1	702.1	712.3	722.4	732.6	742.9	753.2	763.6	774.0	784.5	795.0	805.5	816.1	826.8	837.5
$Stock_{Use}$	1619.4	1640.3	1664.9	1689.6	1714.4	1739.4	1764.4	1789.6	1814.9	1840.3	1865.9	1891.6	1917.4	1943.3	1969.3	1995.5	2021.7	2048.1	2074.6
$\sum L_{Env}$	4.2	11.9	19.7	27.5	35.3	43.1	51.0	58.8	66.7	74.6	82.5	90.5	98.4	106.3	114.2	122.2	130.1	138.1	146.0
$\sum L_{OMF}$	657.9	1324.1	2000.3	2686.4	3382.5	4088.6	4804.9	5531.2	6267.7	7014.4	7771.4	8538.8	9316.5	10104.6	10903.2	11712.3	12531.8	13362.1	14202.9
$\sum L_{LF}$	168.6	337.4	506.2	674.9	843.4	1011.7	1179.6	1347.4	1514.8	1681.8	1848.4	2014.4	2180.0	2344.9	2509.2	2672.8	2835.7	2997.9	3159.2

Table A 55: Results - Polymerization catalysts - In-use dissipation max - Min

In-use dissipation max - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	276.4	278.7	281.0	283.4	285.6	287.9	290.2	292.4	294.7	296.9	299.1	301.3	303.5	305.6	307.8	309.9	312.1	314.2	316.3
$L_{EOL,lf}$	17.3	17.5	17.7	17.9	18.1	18.3	18.5	18.8	19.0	19.2	19.4	19.6	19.8	20.0	20.2	20.4	20.6	20.8	21.0
R_{B2B}	302.4	305.9	309.5	313.0	316.6	320.1	323.7	327.3	330.8	334.4	337.9	341.5	345.0	348.6	352.1	355.7	359.3	362.8	366.4
$L_{MP,OMF}$	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1
$L_{MP,Env}$	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	234.9	237.7	240.5	243.2	246.0	248.7	251.5	254.3	257.0	259.8	262.6	265.3	268.1	270.8	273.6	276.4	279.1	281.9	284.6
$Out_{FM} = In_{Use}$	234.9	237.7	240.5	243.2	246.0	248.7	251.5	254.3	257.0	259.8	262.6	265.3	268.1	270.8	273.6	276.4	279.1	281.9	284.6
$L_{Use,OMF} = In_{F\&M-PET}$	234.9	237.7	240.5	243.2	246.0	248.7	251.5	254.3	257.0	259.8	262.6	265.3	268.1	270.8	273.6	276.4	279.1	281.9	284.6
$Out_{F\&M-PET} = In_{Use-PET}$	537.3	543.6	549.9	556.2	562.6	568.9	575.2	581.5	587.8	594.2	600.5	606.8	613.1	619.4	625.7	632.1	638.4	644.7	651.0
$Out_{Use-PET} = In_{EOL-PET}$	536.1	542.4	548.7	555.0	561.3	567.6	573.9	580.2	586.5	592.8	599.2	605.5	611.8	618.1	624.4	630.7	637.0	643.3	649.6
$L_{MP,env}$	38.7	38.3	37.9	37.4	37.1	36.6	36.1	35.7	35.2	34.6	34.2	33.6	33.0	32.5	31.9	31.4	30.7	30.1	29.5
$L_{Use-PET,env}$	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.4	1.4
$L_{EOL,OMF}$	216.4	219.0	221.5	224.1	226.6	229.1	231.7	234.2	236.8	239.3	241.9	244.4	247.0	249.5	252.0	254.6	257.1	259.7	262.2
$Stock_{Use}$	536.1	542.4	548.7	555.0	561.3	567.6	573.9	580.2	586.5	592.9	599.2	605.5	611.8	618.1	624.4	630.7	637.0	643.3	649.6
$\sum L_{Env}$	2.6	5.2	7.7	10.2	12.8	15.4	18.0	20.5	23.1	25.6	28.1	30.6	33.1	35.7	38.2	40.7	43.2	45.7	48.2
$\sum L_{OMF}$	217.8	438.2	661.0	886.4	1114.4	1344.8	1577.8	1813.2	2051.3	2291.8	2534.9	2780.5	3028.7	3279.4	3532.5	3788.2	4046.4	4307.2	4570.5
$\sum L_{LF}$	56.0	111.8	167.4	222.7	277.9	332.8	387.4	441.8	496.0	549.8	603.4	656.6	709.4	761.9	814.0	865.8	917.1	968.1	1018.6

Table A 56: Results - Polymerization catalysts - In-use dissipation max - Max

In-use dissipation max - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	833.0	842.9	852.7	862.6	872.4	882.3	892.1	902.0	911.8	921.7	931.5	941.3	951.2	961.0	970.8	980.7	990.5	1000.3	1010.1
$L_{EOL,lf}$	52.2	53.0	53.8	54.6	55.4	56.2	57.0	57.8	58.7	59.5	60.3	61.1	62.0	62.8	63.6	64.5	65.3	66.2	67.1
R_{B2B}	911.3	925.1	939.0	952.9	966.9	981.0	995.1	1009.3	1023.6	1038.0	1052.4	1066.8	1081.4	1096.0	1110.7	1125.4	1140.2	1155.1	1170.1
$L_{MP,OMF}$	4.2	4.1	4.1	4.1	4.0	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4
$L_{MP,Env}$	4.2	4.1	4.1	4.1	4.0	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	708.1	718.8	729.6	740.4	751.3	762.2	773.2	784.2	795.3	806.4	817.6	828.9	840.2	851.5	863.0	874.4	885.9	897.5	909.1
$Out_{FM} = In_{Use}$	708.1	718.8	729.6	740.4	751.3	762.2	773.2	784.2	795.3	806.4	817.6	828.9	840.2	851.5	863.0	874.4	885.9	897.5	909.1
$L_{Use,OMF} = In_{F\&M-PET}$	708.1	718.8	729.6	740.4	751.3	762.2	773.2	784.2	795.3	806.4	817.6	828.9	840.2	851.5	863.0	874.4	885.9	897.5	909.1
$Out_{F\&M-PET} = In_{Use-PET}$	1619.4	1643.9	1668.5	1693.3	1718.2	1743.2	1768.3	1793.5	1818.9	1844.4	1870.0	1895.7	1921.6	1947.5	1973.6	1999.8	2026.2	2052.6	2079.2
$Out_{Use-PET} = In_{EOL-PET}$	1615.8	1640.3	1664.9	1689.6	1714.4	1739.3	1764.4	1789.6	1814.9	1840.3	1865.9	1891.6	1917.4	1943.3	1969.3	1995.4	2021.7	2048.1	2074.6
$L_{MP,env}$	116.7	115.8	115.0	114.1	113.1	112.1	111.0	109.9	108.7	107.5	106.2	104.9	103.6	102.1	100.7	99.1	97.6	95.9	94.3
$L_{Use-PET,env}$	3.6	3.6	3.7	3.7	3.8	3.8	3.9	3.9	4.0	4.1	4.1	4.2	4.2	4.3	4.3	4.4	4.5	4.5	4.6
$L_{EOL,OMF}$	652.3	662.1	672.1	682.0	692.1	702.1	712.3	722.4	732.6	742.9	753.2	763.6	774.0	784.5	795.0	805.5	816.1	826.8	837.5
$Stock_{Use}$	1615.8	1640.3	1664.9	1689.6	1714.4	1739.4	1764.4	1789.6	1814.9	1840.3	1865.9	1891.6	1917.4	1943.3	1969.3	1995.5	2021.7	2048.1	2074.6
$\sum L_{Env}$	7.8	15.5	23.3	31.1	38.9	46.7	54.6	62.4	70.3	78.2	86.1	94.1	102.0	109.9	117.8	125.8	133.8	141.7	149.6
$\sum L_{OMF}$	656.5	1322.7	1998.9	2685.0	3381.1	4087.2	4803.5	5529.8	6266.3	7013.0	7770.0	8537.4	9315.1	10103.2	10901.8	11710.9	12530.5	13360.7	14201.5
$\sum L_{LF}$	168.9	337.7	506.5	675.1	843.7	1011.9	1179.9	1347.7	1515.1	1682.1	1848.6	2014.6	2180.2	2345.1	2509.5	2673.1	2836.0	2998.1	3159.5

Table A 57: Results - Polymerization catalysts - EOL collection scenario A - Min

EOL collection scenario A - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	272.2	274.5	276.8	279.1	281.3	283.6	285.8	288.0	290.2	292.4	294.6	296.7	298.9	301.0	303.1	305.3	307.3	309.4	311.5
$L_{EOL,lf}$	17.0	17.2	17.4	17.6	17.8	18.0	18.2	18.4	18.6	18.8	19.0	19.2	19.4	19.6	19.8	20.0	20.2	20.3	20.5
R_{B2B}	305.9	309.5	313.1	316.7	320.3	323.9	327.5	331.1	334.7	338.3	341.9	345.5	349.1	352.7	356.3	359.9	363.5	367.1	370.7
$L_{MP,OMF}$	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1	1.0
$L_{MP,Env}$	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1	1.0
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	231.4	234.1	236.8	239.5	242.3	245.0	247.7	250.4	253.1	255.9	258.6	261.3	264.0	266.7	269.5	272.2	274.9	277.6	280.3
$Out_{FM} = In_{Use}$	231.4	234.1	236.8	239.5	242.3	245.0	247.7	250.4	253.1	255.9	258.6	261.3	264.0	266.7	269.5	272.2	274.9	277.6	280.3
$L_{Use,OMF} = In_{F\&M-PET}$	231.4	234.1	236.8	239.5	242.3	245.0	247.7	250.4	253.1	255.9	258.6	261.3	264.0	266.7	269.5	272.2	274.9	277.6	280.3
$Out_{F\&M-PET} = In_{Use-PET}$	537.3	543.6	549.9	556.2	562.6	568.9	575.2	581.5	587.8	594.2	600.5	606.8	613.1	619.4	625.7	632.1	638.4	644.7	651.0
$Out_{Use-PET} = In_{EOL-PET}$	536.7	543.0	549.3	555.6	561.9	568.3	574.6	580.9	587.2	593.5	599.8	606.1	612.4	618.7	625.1	631.4	637.7	644.0	650.3
$L_{MP,env}$	38.1	37.7	37.3	36.9	36.5	36.0	35.6	35.1	34.6	34.2	33.6	33.0	32.6	32.0	31.5	30.9	30.2	29.7	29.0
$L_{Use-PET,env}$	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
$L_{EOL,OMF}$	213.8	216.3	218.9	221.4	223.9	226.4	228.9	231.4	233.9	236.5	239.0	241.5	244.0	246.5	249.0	251.5	254.1	256.6	259.1
$Stock_{Use}$	536.7	543.0	549.3	555.6	562.0	568.3	574.6	580.9	587.2	593.5	599.8	606.1	612.4	618.7	625.1	631.4	637.7	644.0	650.3
$\sum L_{Env}$	2.0	3.9	5.8	7.8	9.7	11.5	13.4	15.3	17.1	19.0	20.9	22.8	24.7	26.5	28.3	30.1	31.9	33.7	35.4
$\sum L_{OMF}$	215.2	432.8	653.0	875.8	1101.0	1328.6	1558.8	1791.5	2026.6	2264.3	2504.5	2747.2	2992.4	3240.0	3490.1	3742.7	3997.9	4255.6	4515.7
$\sum L_{LF}$	55.1	110.0	164.7	219.2	273.5	327.5	381.3	434.8	488.0	540.9	593.5	645.8	697.8	749.4	800.6	851.5	902.0	951.9	1001.5

Table A 58: Results - Polymerization catalysts - EOL collection scenario A - Max

EOL collection Scenario A - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	820.4	830.1	839.8	849.5	859.2	868.9	878.6	888.3	898.0	907.7	917.4	927.1	936.8	946.5	956.1	965.8	975.5	985.2	994.8
$L_{EOL,lf}$	51.1	51.9	52.7	53.4	54.2	55.0	55.8	56.6	57.4	58.2	59.0	59.8	60.7	61.5	62.3	63.1	64.0	64.8	65.6
R_{B2B}	922.0	936.0	950.0	964.1	978.3	992.5	1006.8	1021.2	1035.6	1050.2	1064.7	1079.4	1094.1	1108.9	1123.7	1138.7	1153.7	1168.7	1183.8
$L_{MP,OMF}$	4.1	4.1	4.0	4.0	4.0	3.9	3.9	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4	3.3
$L_{MP,Env}$	4.1	4.1	4.0	4.0	4.0	3.9	3.9	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4	3.3
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	697.3	707.9	718.5	729.2	739.9	750.7	761.5	772.4	783.3	794.2	805.3	816.4	827.5	838.7	849.9	861.2	872.5	883.9	895.4
$Out_{FM} = In_{Use}$	697.3	707.9	718.5	729.2	739.9	750.7	761.5	772.4	783.3	794.2	805.3	816.4	827.5	838.7	849.9	861.2	872.5	883.9	895.4
$L_{Use,OMF} = In_{F\&M-PET}$	697.3	707.9	718.5	729.2	739.9	750.7	761.5	772.4	783.3	794.2	805.3	816.4	827.5	838.7	849.9	861.2	872.5	883.9	895.4
$Out_{F\&M-PET} = In_{Use-PET}$	1619.4	1643.9	1668.5	1693.3	1718.2	1743.2	1768.3	1793.5	1818.9	1844.4	1870.0	1895.7	1921.6	1947.5	1973.6	1999.8	2026.2	2052.6	2079.2
$Out_{Use-PET} = In_{EOL-PET}$	1617.6	1642.1	1666.7	1691.4	1716.3	1741.3	1766.4	1791.6	1816.9	1842.4	1867.9	1893.6	1919.5	1945.4	1971.5	1997.6	2023.9	2050.4	2076.9
$L_{MP,env}$	114.9	114.1	113.2	112.3	111.3	110.4	109.4	108.3	107.1	105.9	104.6	103.3	102.0	100.6	99.1	97.6	96.1	94.5	92.9
$L_{Use-PET,env}$	1.8	1.8	1.8	1.9	1.9	1.9	1.9	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.2	2.2	2.2	2.3	2.3
$L_{EOL,OMF}$	644.4	654.2	664.0	673.9	683.8	693.7	703.7	713.8	723.9	734.0	744.2	754.4	764.7	775.0	785.4	795.9	806.3	816.9	827.4
$Stock_{Use}$	1617.6	1642.1	1666.7	1691.4	1716.3	1741.3	1766.4	1791.6	1816.9	1842.4	1868.0	1893.7	1919.5	1945.4	1971.5	1997.7	2024.0	2050.4	2076.9
$\sum L_{Env}$	5.9	11.8	17.6	23.5	29.4	35.3	41.1	46.9	52.7	58.5	64.4	70.2	75.9	81.6	87.3	93.0	98.7	104.3	109.9
$\sum L_{OMF}$	648.5	1306.8	1974.8	2652.7	3340.5	4038.2	4745.8	5463.4	6191.1	6928.9	7676.9	8435.0	9203.3	9981.9	10770.8	11570.2	12380.0	13200.2	14030.9
$\sum L_{LF}$	166.0	331.9	497.9	663.5	829.1	994.5	1159.7	1324.6	1489.0	1653.1	1816.8	1979.9	2142.6	2304.7	2466.1	2626.9	2787.0	2946.3	3104.8

Table A 59: Results - Polymerization catalysts - EOL collection scenario C - Min

EOL collection Scenario C - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	279.8	282.1	284.5	286.8	289.2	291.5	293.8	296.0	298.3	300.5	302.8	305.0	307.2	309.4	311.6	313.7	315.9	318.0	320.2
$L_{EOL,lf}$	17.7	17.9	18.1	18.4	18.6	18.8	19.0	19.2	19.4	19.6	19.8	20.0	20.2	20.4	20.7	20.9	21.1	21.3	21.5
R_{B2B}	299.5	303.0	306.5	310.0	313.6	317.1	320.6	324.1	327.7	331.2	334.7	338.2	341.7	345.3	348.8	352.3	355.8	359.3	362.9
$L_{MP,OMF}$	1.4	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1
$L_{MP,Env}$	1.4	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	237.8	240.6	243.4	246.2	249.0	251.8	254.6	257.4	260.2	263.0	265.8	268.6	271.4	274.2	277.0	279.8	282.6	285.4	288.1
$Out_{FM} = In_{Use}$	237.8	240.6	243.4	246.2	249.0	251.8	254.6	257.4	260.2	263.0	265.8	268.6	271.4	274.2	277.0	279.8	282.6	285.4	288.1
$L_{Use,OMF} = In_{F\&M-PET}$	237.8	240.6	243.4	246.2	249.0	251.8	254.6	257.4	260.2	263.0	265.8	268.6	271.4	274.2	277.0	279.8	282.6	285.4	288.1
$Out_{F\&M-PET} = In_{Use-PET}$	537.3	543.6	549.9	556.2	562.6	568.9	575.2	581.5	587.8	594.2	600.5	606.8	613.1	619.4	625.7	632.1	638.4	644.7	651.0
$Out_{Use-PET} = In_{EOL-PET}$	536.7	543.0	549.3	555.6	561.9	568.3	574.6	580.9	587.2	593.5	599.8	606.1	612.4	618.7	625.1	631.4	637.7	644.0	650.3
$L_{MP,env}$	39.2	38.7	38.4	37.9	37.5	37.1	36.6	36.0	35.6	35.1	34.5	34.0	33.4	32.9	32.3	31.7	31.1	30.5	29.9
$L_{Use-PET,env}$	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
$L_{EOL,OMF}$	219.5	222.1	224.7	227.2	229.8	232.4	235.0	237.6	240.1	242.7	245.3	247.9	250.5	253.0	255.6	258.2	260.8	263.4	265.9
$Stock_{Use}$	536.7	543.0	549.3	555.6	562.0	568.3	574.6	580.9	587.2	593.5	599.8	606.1	612.4	618.7	625.1	631.4	637.7	644.0	650.3
$\sum L_{Env}$	2.0	4.0	6.0	7.9	9.8	11.8	13.7	15.6	17.4	19.4	21.3	23.2	25.1	27.0	28.9	30.7	32.5	34.3	36.1
$\sum L_{OMF}$	220.9	444.4	670.5	899.0	1130.1	1363.9	1600.2	1839.1	2080.4	2324.4	2570.9	2820.0	3071.7	3325.9	3582.7	3842.0	4103.9	4368.4	4635.4
$\sum L_{LF}$	56.9	113.5	170.0	226.3	282.4	338.3	393.8	449.1	504.0	558.7	613.1	667.0	720.6	773.9	826.9	879.5	931.7	983.5	1034.9

Table A 60: Results - Polymerization catalysts - EOL collection scenario C - Max

EOL collection Scenario C - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	843.2	853.2	863.2	873.2	883.1	893.1	903.1	913.1	923.0	933.0	942.9	952.9	962.9	972.8	982.8	992.7	1002.6	1012.6	1022.5
$L_{EOL,lf}$	53.4	54.3	55.1	55.9	56.7	57.5	58.4	59.2	60.0	60.9	61.7	62.6	63.4	64.3	65.1	66.0	66.9	67.7	68.6
R_{B2B}	902.6	916.3	930.0	943.8	957.7	971.6	985.6	999.7	1013.8	1028.0	1042.3	1056.7	1071.1	1085.5	1100.1	1114.7	1129.4	1144.1	1158.9
$L_{MP,OMF}$	4.2	4.2	4.2	4.1	4.1	4.1	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4
$L_{MP,Env}$	4.2	4.2	4.2	4.1	4.1	4.1	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	716.8	727.6	738.5	749.5	760.5	771.6	782.7	793.8	805.1	816.4	827.7	839.1	850.5	862.0	873.6	885.2	896.8	908.5	920.3
$Out_{FM} = In_{Use}$	716.8	727.6	738.5	749.5	760.5	771.6	782.7	793.8	805.1	816.4	827.7	839.1	850.5	862.0	873.6	885.2	896.8	908.5	920.3
$L_{Use,OMF} = In_{F\&M-PET}$	716.8	727.6	738.5	749.5	760.5	771.6	782.7	793.8	805.1	816.4	827.7	839.1	850.5	862.0	873.6	885.2	896.8	908.5	920.3
$Out_{F\&M-PET} = In_{Use-PET}$	1619.4	1643.9	1668.5	1693.3	1718.2	1743.2	1768.3	1793.5	1818.9	1844.4	1870.0	1895.7	1921.6	1947.5	1973.6	1999.8	2026.2	2052.6	2079.2
$Out_{Use-PET} = In_{EOL-PET}$	1617.6	1642.1	1666.7	1691.4	1716.3	1741.3	1766.4	1791.6	1816.9	1842.4	1867.9	1893.6	1919.5	1945.4	1971.5	1997.6	2023.9	2050.4	2076.9
$L_{MP,env}$	118.1	117.2	116.4	115.5	114.5	113.5	112.4	111.3	110.0	108.8	107.5	106.2	104.8	103.4	101.9	100.3	98.7	97.2	95.5
$L_{Use-PET,env}$	1.8	1.8	1.8	1.9	1.9	1.9	1.9	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.2	2.2	2.2	2.3	2.3
$L_{EOL,OMF}$	661.5	671.5	681.6	691.7	701.9	712.1	722.4	732.7	743.0	753.5	763.9	774.4	785.0	795.6	806.3	817.0	827.7	838.5	849.4
$Stock_{Use}$	1617.6	1642.1	1666.7	1691.4	1716.3	1741.3	1766.4	1791.6	1816.9	1842.4	1868.0	1893.7	1919.5	1945.4	1971.5	1997.7	2024.0	2050.4	2076.9
$\sum L_{Env}$	6.0	12.0	18.0	24.0	30.0	35.9	41.8	47.8	53.7	59.6	65.6	71.5	77.3	83.1	88.9	94.7	100.5	106.2	111.9
$\sum L_{OMF}$	665.7	1341.4	2027.2	2723.0	3429.0	4145.1	4871.5	5608.2	6355.1	7112.5	7880.3	8658.5	9447.2	10246.5	11056.4	11877.0	12708.3	13550.2	14403.0
$\sum L_{LF}$	171.5	343.0	514.5	685.8	857.1	1028.0	1198.8	1369.3	1539.3	1709.0	1878.3	2047.1	2215.3	2383.0	2550.0	2716.4	2882.0	3046.9	3210.9

Table A 61: Results - Polymerization catalysts - EOL closed-loop recycling Scenario B - Min

EOL closed-loop recycling Scenario B - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	216.6	218.5	220.3	222.1	223.9	225.7	227.5	229.2	231.0	232.7	234.5	236.2	237.9	239.6	241.3	242.9	244.6	246.3	247.9
$L_{EOL,lf}$	13.8	14.0	14.1	14.3	14.5	14.6	14.8	15.0	15.1	15.3	15.4	15.6	15.8	15.9	16.1	16.3	16.4	16.6	16.7
R_{B2B}	353.2	357.3	361.5	365.6	369.8	373.9	378.1	382.2	386.4	390.5	394.7	398.8	403.0	407.1	411.3	415.4	419.6	423.7	427.9
$L_{MP,OMF}$	1.1	1.1	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8
$L_{MP,Env}$	1.1	1.1	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	184.1	186.3	188.5	190.6	192.8	195.0	197.1	199.3	201.5	203.6	205.8	208.0	210.1	212.3	214.5	216.6	218.8	221.0	223.1
$Out_{FM} = In_{Use}$	184.1	186.3	188.5	190.6	192.8	195.0	197.1	199.3	201.5	203.6	205.8	208.0	210.1	212.3	214.5	216.6	218.8	221.0	223.1
$L_{Use,OMF} = In_{F\&M-PET}$	184.1	186.3	188.5	190.6	192.8	195.0	197.1	199.3	201.5	203.6	205.8	208.0	210.1	212.3	214.5	216.6	218.8	221.0	223.1
$Out_{F\&M-PET} = In_{Use-PET}$	537.3	543.6	549.9	556.2	562.6	568.9	575.2	581.5	587.8	594.2	600.5	606.8	613.1	619.4	625.7	632.1	638.4	644.7	651.0
$Out_{Use-PET} = In_{EOL-PET}$	536.7	543.0	549.3	555.6	561.9	568.3	574.6	580.9	587.2	593.5	599.8	606.1	612.4	618.7	625.1	631.4	637.7	644.0	650.3
$L_{MP,env}$	30.3	30.1	29.7	29.4	29.0	28.7	28.3	27.9	27.5	27.2	26.8	26.3	25.9	25.5	25.0	24.5	24.1	23.6	23.1
$L_{Use-PET,env}$	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
$L_{EOL,OMF}$	169.7	171.7	173.7	175.7	177.7	179.7	181.7	183.7	185.7	187.7	189.7	191.7	193.7	195.7	197.7	199.7	201.7	203.7	205.7
$Stock_{Use}$	536.7	543.0	549.3	555.6	562.0	568.3	574.6	580.9	587.2	593.5	599.8	606.1	612.4	618.7	625.1	631.4	637.7	644.0	650.3
$\sum L_{Env}$	1.7	3.4	5.0	6.7	8.3	9.9	11.5	13.1	14.7	16.4	18.0	19.7	21.3	22.9	24.5	26.1	27.7	29.2	30.7
$\sum L_{OMF}$	170.8	343.6	518.3	695.1	873.8	1054.5	1237.2	1421.9	1608.6	1797.3	1987.9	2180.6	2375.2	2571.8	2770.4	2971.0	3173.6	3378.1	3584.6
$\sum L_{LF}$	44.1	88.2	132.0	175.7	219.2	262.4	305.5	348.4	391.1	433.5	475.7	517.6	559.4	600.8	641.9	682.7	723.2	763.4	803.3

Table A 62: Results - Polymerization catalysts - EOL closed-loop recycling Scenario B - Max

EOL closed-loop recycling Scenario B - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	652.9	660.7	668.4	676.1	683.8	691.6	699.3	707.0	714.7	722.4	730.1	737.8	745.6	753.3	761.0	768.7	776.4	784.1	791.8
$L_{EOL,lf}$	41.6	42.3	42.9	43.5	44.2	44.8	45.5	46.1	46.8	47.4	48.1	48.7	49.4	50.1	50.7	51.4	52.1	52.8	53.5
R_{B2B}	1064.4	1080.5	1096.7	1113.0	1129.3	1145.8	1162.3	1178.9	1195.5	1212.3	1229.1	1246.0	1263.0	1280.1	1297.2	1314.5	1331.8	1349.1	1366.6
$L_{MP,OMF}$	3.3	3.2	3.2	3.2	3.2	3.1	3.1	3.1	3.0	3.0	3.0	2.9	2.9	2.9	2.8	2.8	2.7	2.7	2.6
$L_{MP,Env}$	3.3	3.2	3.2	3.2	3.2	3.1	3.1	3.1	3.0	3.0	3.0	2.9	2.9	2.9	2.8	2.8	2.7	2.7	2.6
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	555.0	563.4	571.8	580.3	588.9	597.4	606.0	614.7	623.4	632.1	640.9	649.7	658.6	667.5	676.4	685.4	694.4	703.5	712.6
$Out_{FM} = In_{Use}$	555.0	563.4	571.8	580.3	588.9	597.4	606.0	614.7	623.4	632.1	640.9	649.7	658.6	667.5	676.4	685.4	694.4	703.5	712.6
$L_{Use,OMF} = In_{F\&M-PET}$	555.0	563.4	571.8	580.3	588.9	597.4	606.0	614.7	623.4	632.1	640.9	649.7	658.6	667.5	676.4	685.4	694.4	703.5	712.6
$Out_{F\&M-PET} = In_{Use-PET}$	1619.4	1643.9	1668.5	1693.3	1718.2	1743.2	1768.3	1793.5	1818.9	1844.4	1870.0	1895.7	1921.6	1947.5	1973.6	1999.8	2026.2	2052.6	2079.2
$Out_{Use-PET} = In_{EOL-PET}$	1617.6	1642.1	1666.7	1691.4	1716.3	1741.3	1766.4	1791.6	1816.9	1842.4	1867.9	1893.6	1919.5	1945.4	1971.5	1997.6	2023.9	2050.4	2076.9
$L_{MP,env}$	91.4	90.8	90.1	89.4	88.7	87.8	87.0	86.1	85.2	84.3	83.3	82.2	81.2	80.1	79.0	77.7	76.5	75.2	73.9
$L_{Use-PET,env}$	1.8	1.8	1.8	1.9	1.9	1.9	1.9	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.2	2.2	2.2	2.3	2.3
$L_{EOL,OMF}$	511.6	519.3	527.1	534.9	542.8	550.7	558.6	566.6	574.6	582.7	590.8	598.9	607.1	615.3	623.5	631.8	640.1	648.4	656.8
$Stock_{Use}$	1617.6	1642.1	1666.7	1691.4	1716.3	1741.3	1766.4	1791.6	1816.9	1842.4	1868.0	1893.7	1919.5	1945.4	1971.5	1997.7	2024.0	2050.4	2076.9
$\sum L_{Env}$	5.1	10.1	15.1	20.2	25.3	30.3	35.3	40.4	45.4	50.5	55.5	60.6	65.6	70.5	75.5	80.5	85.5	90.4	95.4
$\sum L_{OMF}$	514.9	1037.4	1567.7	2105.8	2651.8	3205.6	3767.3	4337.0	4914.6	5500.4	6094.1	6696.0	7306.0	7924.1	8550.4	9185.0	9827.9	10478.9	11138.4
$\sum L_{LF}$	133.0	266.1	399.1	532.0	664.8	797.5	929.9	1062.2	1194.2	1325.9	1457.2	1588.2	1718.8	1848.9	1978.6	2107.8	2236.4	2364.4	2491.8

Table A 63: Results - Polymerization catalysts - EOL open-loop recycling Scenario B - Min

EOL open-loop recycling Scenario B - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	276.0	278.3	280.6	283.0	285.2	287.5	289.8	292.0	294.3	296.5	298.7	300.9	303.1	305.2	307.4	309.5	311.6	313.7	315.8
$L_{EOL,lf}$	15.9	16.1	16.3	16.5	16.7	16.9	17.1	17.2	17.4	17.6	17.8	18.0	18.2	18.4	18.6	18.7	18.9	19.1	19.3
R_{B2B}	302.7	306.3	309.8	313.4	316.9	320.5	324.1	327.6	331.2	334.7	338.3	341.9	345.4	349.0	352.5	356.1	359.6	363.2	366.8
$L_{MP,OMF}$	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1
$L_{MP,Env}$	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	234.6	237.4	240.1	242.9	245.6	248.4	251.1	253.9	256.7	259.4	262.2	264.9	267.7	270.5	273.2	276.0	278.7	281.5	284.2
$Out_{FM} = In_{Use}$	234.6	237.4	240.1	242.9	245.6	248.4	251.1	253.9	256.7	259.4	262.2	264.9	267.7	270.5	273.2	276.0	278.7	281.5	284.2
$L_{Use,OMF} = In_{F\&M-PET}$	234.6	237.4	240.1	242.9	245.6	248.4	251.1	253.9	256.7	259.4	262.2	264.9	267.7	270.5	273.2	276.0	278.7	281.5	284.2
$Out_{F\&M-PET} = In_{Use-PET}$	537.3	543.6	549.9	556.2	562.6	568.9	575.2	581.5	587.8	594.2	600.5	606.8	613.1	619.4	625.7	632.1	638.4	644.7	651.0
$Out_{Use-PET} = In_{EOL-PET}$	536.7	543.0	549.3	555.6	561.9	568.3	574.6	580.9	587.2	593.5	599.8	606.1	612.4	618.7	625.1	631.4	637.7	644.0	650.3
$L_{MP,env}$	38.6	38.3	37.8	37.4	37.0	36.5	36.0	35.6	35.1	34.6	34.1	33.5	33.0	32.5	31.9	31.3	30.7	30.1	29.5
$L_{Use-PET,env}$	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
$L_{EOL,OMF}$	218.1	220.6	223.2	225.8	228.3	230.9	233.5	236.0	238.6	241.1	243.7	246.3	248.8	251.4	254.0	256.5	259.1	261.7	264.2
$Stock_{Use}$	536.7	543.0	549.3	555.6	562.0	568.3	574.6	580.9	587.2	593.5	599.8	606.1	612.4	618.7	625.1	631.4	637.7	644.0	650.3
$\sum L_{Env}$	2.0	3.9	5.9	7.8	9.8	11.7	13.5	15.4	17.3	19.2	21.1	23.0	24.9	26.8	28.6	30.4	32.2	34.0	35.7
$\sum L_{OMF}$	219.5	441.4	666.0	893.1	1122.8	1355.0	1589.7	1827.0	2066.9	2309.2	2554.1	2801.6	3051.6	3304.2	3559.3	3816.9	4077.1	4339.9	4605.1
$\sum L_{LF}$	54.5	108.9	163.0	216.9	270.6	324.0	377.1	429.9	482.4	534.6	586.5	638.0	689.2	740.1	790.6	840.6	890.2	939.3	988.1

Table A 64: Results - Polymerization catalysts - EOL open-loop recycling Scenario B - Max

Open-loop recycling Scenario B - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
In_{MP}	831.8	841.7	851.5	861.4	871.2	881.0	890.9	900.7	910.5	920.3	930.2	940.0	949.8	959.6	969.4	979.3	989.1	998.9	1008.7
$L_{EOL,lf}$	48.0	48.8	49.5	50.2	51.0	51.7	52.4	53.2	53.9	54.7	55.5	56.2	57.0	57.8	58.5	59.3	60.1	60.9	61.7
R_{B2B}	912.3	926.1	940.0	954.0	968.0	982.1	996.2	1010.4	1024.7	1039.1	1053.5	1068.0	1082.6	1097.2	1111.9	1126.7	1141.5	1156.4	1171.4
$L_{MP,OMF}$	4.2	4.1	4.1	4.1	4.0	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4
$L_{MP,Env}$	4.2	4.1	4.1	4.1	4.0	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4
$L_{F\&M,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Out_{MP} = In_{FM}$	707.1	717.8	728.5	739.3	750.2	761.1	772.1	783.1	794.2	805.3	816.5	827.7	839.0	850.3	861.7	873.2	884.7	896.2	907.8
$Out_{FM} = In_{Use}$	707.1	717.8	728.5	739.3	750.2	761.1	772.1	783.1	794.2	805.3	816.5	827.7	839.0	850.3	861.7	873.2	884.7	896.2	907.8
$L_{Use,OMF} = In_{F\&M-PET}$	707.1	717.8	728.5	739.3	750.2	761.1	772.1	783.1	794.2	805.3	816.5	827.7	839.0	850.3	861.7	873.2	884.7	896.2	907.8
$Out_{F\&M-PET} = In_{Use-PET}$	1619.4	1643.9	1668.5	1693.3	1718.2	1743.2	1768.3	1793.5	1818.9	1844.4	1870.0	1895.7	1921.6	1947.5	1973.6	1999.8	2026.2	2052.6	2079.2
$Out_{Use-PET} = In_{EOL-PET}$	1617.6	1642.1	1666.7	1691.4	1716.3	1741.3	1766.4	1791.6	1816.9	1842.4	1867.9	1893.6	1919.5	1945.4	1971.5	1997.6	2023.9	2050.4	2076.9
$L_{MP,env}$	116.5	115.6	114.8	113.9	112.9	111.9	110.9	109.8	108.5	107.3	106.1	104.8	103.4	102.0	100.5	99.0	97.4	95.9	94.2
$L_{Use-PET,env}$	1.8	1.8	1.8	1.9	1.9	1.9	1.9	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.2	2.2	2.2	2.3	2.3
$L_{EOL,OMF}$	657.2	667.2	677.2	687.2	697.3	707.5	717.7	727.9	738.2	748.6	759.0	769.4	779.9	790.4	801.0	811.7	822.4	833.1	843.9
$Stock_{Use}$	1617.6	1642.1	1666.7	1691.4	1716.3	1741.3	1766.4	1791.6	1816.9	1842.4	1868.0	1893.7	1919.5	1945.4	1971.5	1997.7	2024.0	2050.4	2076.9
$\sum L_{Env}$	6.0	11.9	17.8	23.8	29.7	35.6	41.4	47.4	53.2	59.1	65.0	70.8	76.6	82.3	88.1	93.9	99.6	105.3	110.9
$\sum L_{OMF}$	661.4	1332.7	2014.0	2705.3	3406.6	4118.1	4839.7	5571.6	6313.6	7066.1	7828.9	8602.0	9385.6	10179.6	10984.2	11799.5	12625.4	13461.9	14309.1
$\sum L_{LF}$	164.5	328.9	493.2	657.3	821.2	984.8	1148.1	1311.1	1473.5	1635.5	1797.2	1958.2	2118.6	2278.4	2437.4	2595.8	2753.3	2910.0	3065.9

Appendix C) TBC: Case study data and results

Data

Table A 65: Stock of aircrafts of major German airlines in 2012/2013 (Lufthansa AG 2013; AirBerlin 2013; Condor 2013; Germanwings 2013; TUIfly 2013)

Manufacturer	Type	Number of planes	Number of engines per plane	Sum of engines	Distance		
Lufthansa					**Short**	**Mid**	**Long**
Airbus	A380-800	10	4	40			x
Boeing	747-8	4	4	16			x
Boeing	747-400	25	4	100			x
Airbus	A340-600	24	4	96			x
Airbus	A340-300	24	4	96			x
Airbus	A330-300	18	2	36			x
Boeing	737-800 IGW	3	2	6			x
Airbus	A321-100/200	62	2	124	x	x	
Airbus	A320-200	49	2	98	x	x	
Airbus	A319-100	35	2	70	x	x	
Boeing	737-500	30	2	60	x	x	
Boeing	737-300	43	2	86	x	x	
Embraer	ERJ-195	19	2	38	x	x	
Embraer	ERJ-190	9	2	18	x	x	
Bombardier	CRJ900	12	2	24	x	x	
Bombardier	CRJ700/200	20	2	40	x	x	
ATR	72-500	11	2	22	x	x	
Bombardier	Dash 8 Q400	14	2	28	x	x	
McDonnell Douglas/Boeing	MD-11F	18	3	54	x	x	
Air Berlin					**Short**	**Mid**	**Long**
Airbus	A330-300	2	2	4		x	
Airbus	A330-200	13	2	26		x	x
Airbus	A321-200	12	2	24		x	
Airbus	A320-200	27	2	54		x	
Airbus	A319-112	1	2	2	x		
Boeing	737-800	36	2	72	x	x	
Boeing	737-700	18	2	36	x	x	
Bombardier	Dash 8 Q400	10	2	20	x		
Condor					**Short**	**Mid**	**Long**
Airbus	A320-200	12	2	24	x	x	
Airbus	A321-200	1	2	2	x	x	
Boeing	757-300	13	2	26	x	x	
Boeing	767-300ER	12	2	24			x
GermanWings					**Short**	**Mid**	**Long**
Airbus	A319-100	32	2	64	x	x	
TUIfly					**Short**	**Mid**	**Long**
Boeing	737-700	10	2	20	x	x	
Boeing	737-800	25	2	50	x	x	

Table A 66: Development of aircraft engine stock over time

Scenario	Min (Growth rate 2.5%)			Max (Growth rate 3.5%)		
Year/ Distance	Short	Mid	Long	Short	Mid	Long
2012	500	573	427	500	573	427
2013	513	587	438	518	593	442
2014	525	602	449	536	614	457
2015	538	617	460	554	635	473
2016	552	632	471	574	658	490
2017	566	648	483	594	681	507
2018	580	665	495	615	704	525
2019	594	681	508	636	729	543
2020	609	698	520	658	755	562
2021	624	716	533	681	781	582
2022	640	733	547	705	808	602
2023	656	752	560	730	837	623
2024	672	771	574	756	866	645
2025	689	790	589	782	896	668
2026	706	810	603	809	928	691
2027	724	830	618	838	960	715
2028	742	851	634	867	994	740
2029	761	872	650	897	1028	766
2030	780	894	666	929	1064	793

Results

In the following, the results for the different scenarios which have been analyzed regarding the life cycle of TBC as summarized in Table 73 are presented. The abbreviations and notations are explicated in the following table.

Table A 67: Abbreviations and notations of stocks and flows used in TBC case study

Flow	**Parameter**
Input flow to coating	$Out_{FM-I} = In_{FM-II}$
Input flow to use phase	$Out_{FM-I} = In_{Use}$
Input flow to spray powder production	$Out_{MP} = In_{FM-I}$
Input flow to EOL phase	$Out_{Use-II} = In_{EOL}$
Input flow to maintenance	$Out_{Use-I} = In_{Use-II}$
Dissipative losses from EOL to landfills	$L_{EOL,lf}$
Dissipative losses from EOL to other material flows	$L_{EOL,omf}$
Dissipative losses from spray powder production to landfills	$L_{FM-I,LF}$
Dissipative losses from coating to landfills	$L_{FM-II,LF}$
Dissipative losses from coating to other material flows	$L_{FM-II,omf}$
Dissipative losses from material production to environment	$L_{MP,Env}$
Dissipative losses from material production to landfills	$L_{MP,lf}$
Dissipative losses from material production to other material flows	$L_{MP,omf}$
Dissipative losses from use aircraft operations to environment	$L_{Use-I,env}$
Dissipative losses from maintenance to landfills	$L_{Use-II,lf}$
Dissipative losses from maintenance to other material flows	$L_{Use-II,OMF}$
Input flows to material production (environment to technosphere)	In_{MP}
Stock	
In-Use stock	$Stock_{Use}$
Cumulative dissipative losses to environment (accumulated starting from 2012)	$\sum L_{Env}$
Cumulative dissipative losses to other material flows (accumulated starting from 2012)	$\sum L_{OMF}$
Cumulative dissipative losses to landfills (accumulated starting from 2012)	$\sum L_{LF}$

Table A 68: Results - TBC - Baseline-Scenario - Min

Baseline-Scenario - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	378.8	409.5	406.6	403.7	408.5	406.2	416.0	426.3	424.3	422.4	420.6	418.8	417.1	415.5	414.0	412.6	411.2	409.9	408.6
$Out_{FM-I} = In_{Use}$	140.5	153.4	153.7	154.0	157.3	157.8	163.1	168.6	169.3	170.0	170.7	171.5	172.3	173.1	173.9	174.7	175.6	176.4	177.3
$Out_{MP} = In_{FM-I}$	398.8	431.1	428.0	425.0	430.0	427.6	437.9	448.7	446.6	444.6	442.7	440.9	439.1	437.4	435.8	434.3	432.8	431.4	430.1
$Out_{Use-II} = In_{EOL}$	68.2	68.2	68.2	68.2	69.6	69.7	72.1	74.6	74.7	74.9	75.0	75.2	75.4	75.6	75.8	76.0	76.1	76.3	76.5
$Out_{Use-I} = In_{Use-II}$	136.3	136.3	136.3	136.3	139.1	139.3	144.1	149.1	149.4	149.8	150.1	150.4	150.8	151.2	151.5	151.9	152.3	152.7	153.1
$L_{EOL,lf}$	6.8	6.8	6.8	6.8	7.0	7.0	7.2	7.5	7.5	7.5	7.5	7.5	7.5	7.6	7.6	7.6	7.6	7.6	7.7
$L_{EOL,omf}$	61.3	61.3	61.3	61.3	62.6	62.7	64.9	67.1	67.2	67.4	67.5	67.7	67.9	68.0	68.2	68.4	68.5	68.7	68.9
$L_{FM-I,LF}$	19.9	21.6	21.4	21.2	21.5	21.4	21.9	22.4	22.3	22.2	22.1	22.0	22.0	21.9	21.8	21.7	21.6	21.6	21.5
$L_{FM-II,LF}$	23.8	25.6	25.3	25.0	25.1	24.8	25.3	25.8	25.5	25.2	25.0	24.7	24.5	24.2	24.0	23.8	23.6	23.3	23.1
$L_{FM-II,omf}$	214.5	230.5	227.6	224.7	226.1	223.5	227.6	231.9	229.5	227.1	224.8	222.6	220.4	218.2	216.1	214.1	212.0	210.1	208.2
$L_{MP,Env}$	1.7	1.8	1.7	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.1	1.1
$L_{MP,lf}$	151.8	160.9	156.7	152.6	151.3	147.5	148.1	148.7	145.0	141.3	137.8	134.3	131.0	127.7	124.4	121.3	118.2	115.1	112.2
$L_{MP,omf}$	1.7	1.8	1.7	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.1	1.1
$L_{Use-I,env}$	4.2	4.6	4.6	4.6	4.7	4.7	4.9	5.1	5.1	5.1	5.1	5.1	5.2	5.2	5.2	5.2	5.3	5.3	5.3
$L_{Use-II,lf}$	37.8	37.8	37.8	37.8	38.6	38.6	39.9	41.3	41.4	41.5	41.6	41.7	41.8	41.9	42.0	42.1	42.2	42.3	42.4
$L_{Use-II,OMF}$	30.4	30.4	30.4	30.4	31.0	31.0	32.1	33.2	33.3	33.4	33.4	33.5	33.6	33.7	33.8	33.8	33.9	34.0	34.1
In_{MP}	553.9	595.5	588.1	580.8	584.5	578.2	589.1	600.5	594.6	588.9	583.4	578.0	572.7	567.7	562.7	557.9	553.3	548.8	544.5
$Stock_{Use}$	497.5	510.0	522.7	535.8	549.2	562.9	577.0	591.4	606.2	621.3	636.9	652.8	669.1	685.8	703.0	720.6	738.6	757.0	776.0
$\sum L_{Env}$	5.9	12.2	18.5	24.8	31.1	37.5	43.9	50.5	57.1	63.7	70.3	76.8	83.3	89.8	96.2	102.7	109.1	115.6	122.0
$\sum L_{OMF}$	307.8	631.9	952.9	1271.0	1592.3	1911.2	2237.4	2571.2	2902.7	3232.1	3559.3	3884.5	4207.7	4528.9	4848.2	5165.7	5481.3	5795.3	6107.5
$\sum L_{LF}$	240.1	523.2	801.6	1075.3	1349.8	1620.2	1894.7	2173.6	2448.5	2719.7	2987.2	3251.0	3511.4	3768.3	4021.9	4272.2	4519.3	4763.3	5004.3

Table A 69: Results - TBC - Baseline-Scenario - Max

Baseline-Scenario - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	645.4	723.5	740.2	758.1	768.7	774.5	778.2	780.9	782.9	784.6	786.1	787.4	788.6	789.8	791.1	792.6	794.1	795.9	797.9
$Out_{FM-I} = In_{Use}$	239.5	271.0	279.8	289.2	295.9	300.9	305.1	308.8	312.4	315.8	319.1	322.4	325.7	329.0	332.3	335.6	339.1	342.6	346.3
$Out_{MP} = In_{FM-I}$	679.4	761.6	779.1	798.0	809.1	815.3	819.2	822.0	824.1	825.9	827.4	828.8	830.1	831.4	832.8	834.3	835.9	837.8	839.9
$Out_{Use-II} = In_{EOL}$	116.1	116.1	119.9	123.9	126.6	128.4	129.8	131.0	132.1	133.0	134.0	134.8	135.7	136.5	137.3	138.1	138.9	139.7	140.5
$Out_{Use-I} = In_{Use-II}$	232.3	232.3	239.8	247.8	253.2	256.8	259.6	262.0	264.1	266.1	267.9	269.7	271.3	272.9	274.5	276.1	277.7	279.4	281.1
$L_{EOL,lf}$	11.6	11.6	12.0	12.4	12.7	12.8	13.0	13.1	13.2	13.3	13.4	13.5	13.6	13.6	13.7	13.8	13.9	14.0	14.1
$L_{EOL,omf}$	104.5	104.5	107.9	111.5	113.9	115.6	116.8	117.9	118.9	119.7	120.6	121.3	122.1	122.8	123.5	124.3	125.0	125.7	126.5
$L_{FM-I,LF}$	34.0	38.1	39.0	39.9	40.5	40.8	41.0	41.1	41.2	41.3	41.4	41.4	41.5	41.6	41.6	41.7	41.8	41.9	42.0
$L_{FM-II,LF}$	40.6	45.3	46.0	46.9	47.3	47.4	47.3	47.2	47.1	46.9	46.7	46.5	46.3	46.1	45.9	45.7	45.5	45.3	45.2
$L_{FM-II,omf}$	365.4	407.3	414.4	422.0	425.5	426.3	425.8	424.8	423.5	421.9	420.2	418.4	416.6	414.8	413.0	411.2	409.5	407.9	406.5
$L_{MP,Env}$	2.8	3.1	3.1	3.1	3.1	3.0	2.9	2.9	2.8	2.7	2.7	2.6	2.5	2.5	2.4	2.3	2.3	2.2	2.1
$L_{MP,lf}$	258.6	284.3	285.3	286.5	284.8	281.3	277.0	272.3	267.5	262.5	257.6	252.6	247.6	242.6	237.8	233.0	228.2	223.6	219.0
$L_{MP,omf}$	2.8	3.1	3.1	3.1	3.1	3.0	2.9	2.9	2.8	2.7	2.7	2.6	2.5	2.5	2.4	2.3	2.3	2.2	2.1
$L_{Use-I,env}$	7.2	8.1	8.4	8.7	8.9	9.0	9.2	9.3	9.4	9.5	9.6	9.7	9.8	9.9	10.0	10.1	10.2	10.3	10.4
$L_{Use-II,lf}$	64.4	64.4	66.5	68.7	70.2	71.2	72.0	72.6	73.2	73.8	74.3	74.7	75.2	75.7	76.1	76.5	77.0	77.4	77.9
$L_{Use-II,OMF}$	51.8	51.8	53.4	55.2	56.4	57.2	57.8	58.4	58.9	59.3	59.7	60.1	60.4	60.8	61.2	61.5	61.9	62.2	62.6
In_{MP}	943.6	1052.1	1070.6	1090.6	1100.0	1102.6	1102.0	1100.0	1097.2	1093.9	1090.3	1086.6	1082.7	1079.0	1075.3	1071.9	1068.7	1065.8	1063.2
$Stock_{Use}$	873.0	903.6	935.2	967.9	1001.8	1036.9	1073.2	1110.7	1149.6	1189.8	1231.5	1274.6	1319.2	1365.4	1413.2	1462.6	1513.8	1566.8	1621.6
$\sum L_{Env}$	10.0	21.2	32.7	44.5	56.4	68.5	80.5	92.7	104.9	117.1	129.3	141.6	153.9	166.2	178.6	191.0	203.4	215.9	228.4
$\sum L_{OMF}$	524.5	1091.2	1669.9	2261.7	2860.6	3462.7	4066.1	4670.1	5274.1	5877.8	6480.9	7083.4	7685.1	8285.9	8886.0	9485.3	10084.0	10682.1	11279.8
$\sum L_{LF}$	409.1	852.8	1301.5	1755.8	2211.2	2664.6	3114.8	3561.2	4003.3	4441.1	4874.4	5303.1	5727.3	6146.9	6562.0	6972.7	7379.1	7781.3	8179.4

Table A 70: Results - TBC - Material production alternative - Pessimistic - Min

Material production alternative (Pessimistic) - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	378.8	409.5	406.6	403.7	408.5	406.2	416.0	426.3	424.3	422.4	420.6	418.8	417.1	415.5	414.0	412.6	411.2	409.9	408.6
$Out_{FM-I} = In_{Use}$	140.5	153.4	153.7	154.0	157.3	157.8	163.1	168.6	169.3	170.0	170.7	171.5	172.3	173.1	173.9	174.7	175.6	176.4	177.3
$Out_{MP} = In_{FM-I}$	398.8	431.1	428.0	425.0	430.0	427.6	437.9	448.7	446.6	444.6	442.7	440.9	439.1	437.4	435.8	434.3	432.8	431.4	430.1
$Out_{Use-II} = In_{EOL}$	68.2	68.2	68.2	68.2	69.6	69.7	72.1	74.6	74.7	74.9	75.0	75.2	75.4	75.6	75.8	76.0	76.1	76.3	76.5
$Out_{Use-I} = In_{Use-II}$	136.3	136.3	136.3	136.3	139.1	139.3	144.1	149.1	149.4	149.8	150.1	150.4	150.8	151.2	151.5	151.9	152.3	152.7	153.1
$L_{EOL,lf}$	6.8	6.8	6.8	6.8	7.0	7.0	7.2	7.5	7.5	7.5	7.5	7.5	7.5	7.6	7.6	7.6	7.6	7.6	7.7
$L_{EOL,omf}$	61.3	61.3	61.3	61.3	62.6	62.7	64.9	67.1	67.2	67.4	67.5	67.7	67.9	68.0	68.2	68.4	68.5	68.7	68.9
$L_{FM-I,LF}$	19.9	21.6	21.4	21.2	21.5	21.4	21.9	22.4	22.3	22.2	22.1	22.0	22.0	21.9	21.8	21.7	21.6	21.6	21.5
$L_{FM-II,LF}$	23.8	25.6	25.3	25.0	25.1	24.8	25.3	25.8	25.5	25.2	25.0	24.7	24.5	24.2	24.0	23.8	23.6	23.3	23.1
$L_{FM-II,omf}$	214.5	230.5	227.6	224.7	226.1	223.5	227.6	231.9	229.5	227.1	224.8	222.6	220.4	218.2	216.1	214.1	212.0	210.1	208.2
$L_{MP,Env}$	4.0	4.3	4.3	4.2	4.3	4.3	4.4	4.5	4.5	4.4	4.4	4.4	4.4	4.4	4.4	4.3	4.3	4.3	4.3
$L_{MP,lf}$	390.8	422.5	419.4	416.5	421.4	419.0	429.2	439.7	437.7	435.7	433.8	432.0	430.3	428.7	427.1	425.6	424.2	422.8	421.5
$L_{MP,omf}$	4.0	4.3	4.3	4.2	4.3	4.3	4.4	4.5	4.5	4.4	4.4	4.4	4.4	4.4	4.4	4.3	4.3	4.3	4.3
$L_{Use-I,env}$	4.2	4.6	4.6	4.6	4.7	4.7	4.9	5.1	5.1	5.1	5.1	5.1	5.2	5.2	5.2	5.2	5.3	5.3	5.3
$L_{Use-II,lf}$	37.8	37.8	37.8	37.8	38.6	38.6	39.9	41.3	41.4	41.5	41.6	41.7	41.8	41.9	42.0	42.1	42.2	42.3	42.4
$L_{Use-II,OMF}$	30.4	30.4	30.4	30.4	31.0	31.0	32.1	33.2	33.3	33.4	33.4	33.5	33.6	33.7	33.8	33.8	33.9	34.0	34.1
In_{MP}	797.6	862.2	856.0	849.9	859.9	855.1	875.8	897.4	893.3	889.2	885.4	881.7	878.2	874.8	871.6	868.5	865.6	862.9	860.3
$Stock_{Use}$	497.5	510.0	522.7	535.8	549.2	562.9	577.0	591.4	606.2	621.3	636.9	652.8	669.1	685.8	703.0	720.6	738.6	757.0	776.0
$\sum L_{Env}$	8.2	17.1	26.0	34.9	43.9	52.9	62.2	71.7	81.3	90.8	100.4	109.9	119.5	129.0	138.6	148.2	157.8	167.4	177.0
$\sum L_{OMF}$	310.2	636.8	960.4	1281.1	1605.1	1926.6	2255.6	2592.4	2926.9	3259.2	3589.4	3917.6	4243.9	4568.2	4890.6	5211.2	5530.0	5847.1	6162.6
$\sum L_{LF}$	479.2	1023.8	1564.9	2102.6	2647.1	3188.9	3744.6	4314.5	4882.2	5447.8	6011.3	6572.9	7132.5	7690.5	8246.7	8801.3	9354.4	9906.1	10456.5

Table A 71: Results - TBC - Material production alternative - Pessimistic - Max

Material production alternative (Pessimistic) - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	645.4	723.5	740.2	758.1	768.7	774.5	778.2	780.9	782.9	784.6	786.1	787.4	788.6	789.8	791.1	792.6	794.1	795.9	797.9
$Out_{FM-I} = In_{Use}$	239.5	271.0	279.8	289.2	295.9	300.9	305.1	308.8	312.4	315.8	319.1	322.4	325.7	329.0	332.3	335.6	339.1	342.6	346.3
$Out_{MP} = In_{FM-I}$	679.4	761.6	779.1	798.0	809.1	815.3	819.2	822.0	824.1	825.9	827.4	828.8	830.1	831.4	832.8	834.3	835.9	837.8	839.9
$Out_{Use-II} = In_{EOL}$	116.1	116.1	119.9	123.9	126.6	128.4	129.8	131.0	132.1	133.0	134.0	134.8	135.7	136.5	137.3	138.1	138.9	139.7	140.5
$Out_{Use-I} = In_{Use-II}$	232.3	232.3	239.8	247.8	253.2	256.8	259.6	262.0	264.1	266.1	267.9	269.7	271.3	272.9	274.5	276.1	277.7	279.4	281.1
$L_{EOL,lf}$	11.6	11.6	12.0	12.4	12.7	12.8	13.0	13.1	13.2	13.3	13.4	13.5	13.6	13.6	13.7	13.8	13.9	14.0	14.1
$L_{EOL,omf}$	104.5	104.5	107.9	111.5	113.9	115.6	116.8	117.9	118.9	119.7	120.6	121.3	122.1	122.8	123.5	124.3	125.0	125.7	126.5
$L_{FM-I,LF}$	34.0	38.1	39.0	39.9	40.5	40.8	41.0	41.1	41.2	41.3	41.4	41.4	41.5	41.6	41.6	41.7	41.8	41.9	42.0
$L_{FM-II,LF}$	40.6	45.3	46.0	46.9	47.3	47.4	47.3	47.2	47.1	46.9	46.7	46.5	46.3	46.1	45.9	45.7	45.5	45.3	45.2
$L_{FM-II,omf}$	365.4	407.3	414.4	422.0	425.5	426.3	425.8	424.8	423.5	421.9	420.2	418.4	416.6	414.8	413.0	411.2	409.5	407.9	406.5
$L_{MP,Env}$	6.8	7.6	7.8	8.0	8.1	8.2	8.2	8.2	8.2	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.4	8.4	8.4
$L_{MP,lf}$	665.8	746.4	763.6	782.0	793.0	799.0	802.8	805.5	807.6	809.4	810.9	812.2	813.5	814.8	816.1	817.6	819.2	821.1	823.1
$L_{MP,omf}$	6.8	7.6	7.8	8.0	8.1	8.2	8.2	8.2	8.2	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.4	8.4	8.4
$L_{Use-I,env}$	7.2	8.1	8.4	8.7	8.9	9.0	9.2	9.3	9.4	9.5	9.6	9.7	9.8	9.9	10.0	10.1	10.2	10.3	10.4
$L_{Use-II,lf}$	64.4	64.4	66.5	68.7	70.2	71.2	72.0	72.6	73.2	73.8	74.3	74.7	75.2	75.7	76.1	76.5	77.0	77.4	77.9
$L_{Use-II,OMF}$	51.8	51.8	53.4	55.2	56.4	57.2	57.8	58.4	58.9	59.3	59.7	60.1	60.4	60.8	61.2	61.5	61.9	62.2	62.6
In_{MP}	1358.8	1523.2	1558.3	1596.0	1618.3	1630.6	1638.4	1643.9	1648.3	1651.8	1654.9	1657.6	1660.2	1662.8	1665.6	1668.6	1671.9	1675.6	1679.8
$Stock_{Use}$	873.0	903.6	935.2	967.9	1001.8	1036.9	1073.2	1110.7	1149.6	1189.8	1231.5	1274.6	1319.2	1365.4	1413.2	1462.6	1513.8	1566.8	1621.6
$\sum L_{Env}$	14.0	29.7	45.9	62.6	79.5	96.7	114.1	131.5	149.2	166.9	184.7	202.7	220.8	239.0	257.2	275.7	294.2	312.9	331.6
$\sum L_{OMF}$	528.5	1099.7	1683.1	2279.8	2883.7	3490.9	4099.6	4709.0	5318.4	5927.6	6536.4	7144.5	7752.0	8358.7	8964.7	9570.0	10174.8	10779.1	11383.0
$\sum L_{LF}$	816.4	1722.1	2649.1	3599.0	4562.5	5533.7	6509.7	7489.3	8471.6	9456.2	10442.9	11431.3	12421.3	13413.0	14406.5	15401.9	16399.3	17398.9	18401.2

Table A 72: Results - TBC - Material production alternative - Optimistic- Min

Material production alternative (Optimistic) - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	378.8	409.5	406.6	403.7	408.5	406.2	416.0	426.3	424.3	422.4	420.6	418.8	417.1	415.5	414.0	412.6	411.2	409.9	408.6
$Out_{FM-I} = In_{Use}$	140.5	153.4	153.7	154.0	157.3	157.8	163.1	168.6	169.3	170.0	170.7	171.5	172.3	173.1	173.9	174.7	175.6	176.4	177.3
$Out_{MP} = In_{FM-I}$	398.8	431.1	428.0	425.0	430.0	427.6	437.9	448.7	446.6	444.6	442.7	440.9	439.1	437.4	435.8	434.3	432.8	431.4	430.1
$Out_{Use-II} = In_{EOL}$	68.2	68.2	68.2	68.2	69.6	69.7	72.1	74.6	74.7	74.9	75.0	75.2	75.4	75.6	75.8	76.0	76.1	76.3	76.5
$Out_{Use-I} = In_{Use-II}$	136.3	136.3	136.3	136.3	139.1	139.3	144.1	149.1	149.4	149.8	150.1	150.4	150.8	151.2	151.5	151.9	152.3	152.7	153.1
$L_{EOL,lf}$	6.8	6.8	6.8	6.8	7.0	7.0	7.2	7.5	7.5	7.5	7.5	7.5	7.5	7.6	7.6	7.6	7.6	7.6	7.7
$L_{EOL,omf}$	61.3	61.3	61.3	61.3	62.6	62.7	64.9	67.1	67.2	67.4	67.5	67.7	67.9	68.0	68.2	68.4	68.5	68.7	68.9
$L_{FM-I,LF}$	19.9	21.6	21.4	21.2	21.5	21.4	21.9	22.4	22.3	22.2	22.1	22.0	22.0	21.9	21.8	21.7	21.6	21.6	21.5
$L_{FM-II,LF}$	23.8	25.6	25.3	25.0	25.1	24.8	25.3	25.8	25.5	25.2	25.0	24.7	24.5	24.2	24.0	23.8	23.6	23.3	23.1
$L_{FM-II,omf}$	214.5	230.5	227.6	224.7	226.1	223.5	227.6	231.9	229.5	227.1	224.8	222.6	220.4	218.2	216.1	214.1	212.0	210.1	208.2
$L_{MP,Env}$	1.7	1.7	1.6	1.5	1.5	1.4	1.3	1.3	1.2	1.1	1.0	1.0	0.9	0.8	0.8	0.7	0.6	0.6	0.5
$L_{MP,lf}$	151.8	157.8	150.5	143.5	139.3	132.8	130.2	127.6	121.4	115.4	109.5	103.8	98.3	92.9	87.7	82.6	77.6	72.8	68.1
$L_{MP,omf}$	1.7	1.7	1.6	1.5	1.5	1.4	1.3	1.3	1.2	1.1	1.0	1.0	0.9	0.8	0.8	0.7	0.6	0.6	0.5
$L_{Use-I,env}$	4.2	4.6	4.6	4.6	4.7	4.7	4.9	5.1	5.1	5.1	5.1	5.1	5.2	5.2	5.2	5.2	5.3	5.3	5.3
$L_{Use-II,lf}$	37.8	37.8	37.8	37.8	38.6	38.6	39.9	41.3	41.4	41.5	41.6	41.7	41.8	41.9	42.0	42.1	42.2	42.3	42.4
$L_{Use-II,OMF}$	30.4	30.4	30.4	30.4	31.0	31.0	32.1	33.2	33.3	33.4	33.4	33.5	33.6	33.7	33.8	33.8	33.9	34.0	34.1
In_{MP}	553.9	592.3	581.7	571.5	572.1	563.1	570.8	578.9	570.5	562.2	554.3	546.6	539.2	532.0	525.0	518.2	511.7	505.4	499.2
$Stock_{Use}$	497.5	510.0	522.7	535.8	549.2	562.9	577.0	591.4	606.2	621.3	636.9	652.8	669.1	685.8	703.0	720.6	738.6	757.0	776.0
$\sum L_{Env}$	5.9	12.2	18.4	24.6	30.7	36.9	43.1	49.4	55.7	61.9	68.1	74.2	80.3	86.3	92.3	98.2	104.1	110.0	115.8
$\sum L_{OMF}$	307.8	631.8	952.8	1270.8	1591.9	1910.6	2236.5	2570.1	2901.3	3230.3	3557.2	3881.9	4204.7	4525.4	4844.2	5161.2	5476.3	5789.7	6101.3
$\sum L_{LF}$	240.1	520.0	792.2	1056.9	1319.3	1574.9	1831.6	2089.5	2340.9	2586.1	2825.3	3058.6	3286.3	3508.4	3725.2	3936.8	4143.4	4345.1	4542.0

Table A 73: Results - TBC - Material production alternative – Optimistic – Max

Material production alternative (Optimistic) - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	645.4	723.5	740.2	758.1	768.7	774.5	778.2	780.9	782.9	784.6	786.1	787.4	788.6	789.8	791.1	792.6	794.1	795.9	797.9
$Out_{FM-I} = In_{Use}$	239.5	271.0	279.8	289.2	295.9	300.9	305.1	308.8	312.4	315.8	319.1	322.4	325.7	329.0	332.3	335.6	339.1	342.6	346.3
$Out_{MP} = In_{FM-I}$	679.4	761.6	779.1	798.0	809.1	815.3	819.2	822.0	824.1	825.9	827.4	828.8	830.1	831.4	832.8	834.3	835.9	837.8	839.9
$Out_{Use-II} = In_{EOL}$	116.1	116.1	119.9	123.9	126.6	128.4	129.8	131.0	132.1	133.0	134.0	134.8	135.7	136.5	137.3	138.1	138.9	139.7	140.5
$Out_{Use-I} = In_{Use-II}$	232.3	232.3	239.8	247.8	253.2	256.8	259.6	262.0	264.1	266.1	267.9	269.7	271.3	272.9	274.5	276.1	277.7	279.4	281.1
$L_{EOL,lf}$	11.6	11.6	12.0	12.4	12.7	12.8	13.0	13.1	13.2	13.3	13.4	13.5	13.6	13.6	13.7	13.8	13.9	14.0	14.1
$L_{EOL,omf}$	104.5	104.5	107.9	111.5	113.9	115.6	116.8	117.9	118.9	119.7	120.6	121.3	122.1	122.8	123.5	124.3	125.0	125.7	126.5
$L_{FM-I,LF}$	34.0	38.1	39.0	39.9	40.5	40.8	41.0	41.1	41.2	41.3	41.4	41.4	41.5	41.6	41.6	41.7	41.8	41.9	42.0
$L_{FM-II,LF}$	40.6	45.3	46.0	46.9	47.3	47.4	47.3	47.2	47.1	46.9	46.7	46.5	46.3	46.1	45.9	45.7	45.5	45.3	45.2
$L_{FM-II,omf}$	365.4	407.3	414.4	422.0	425.5	426.3	425.8	424.8	423.5	421.9	420.2	418.4	416.6	414.8	413.0	411.2	409.5	407.9	406.5
$L_{MP,Env}$	2.8	3.0	2.9	2.9	2.8	2.6	2.5	2.4	2.2	2.1	2.0	1.8	1.7	1.6	1.4	1.3	1.2	1.1	1.0
$L_{MP,lf}$	258.6	278.7	274.0	269.4	262.1	253.2	243.6	233.8	224.0	214.3	204.7	195.2	185.8	176.6	167.5	158.6	149.9	141.4	133.0
$L_{MP,omf}$	2.8	3.0	2.9	2.9	2.8	2.6	2.5	2.4	2.2	2.1	2.0	1.8	1.7	1.6	1.4	1.3	1.2	1.1	1.0
$L_{Use-I,env}$	7.2	8.1	8.4	8.7	8.9	9.0	9.2	9.3	9.4	9.5	9.6	9.7	9.8	9.9	10.0	10.1	10.2	10.3	10.4
$L_{Use-II,lf}$	64.4	64.4	66.5	68.7	70.2	71.2	72.0	72.6	73.2	73.8	74.3	74.7	75.2	75.7	76.1	76.5	77.0	77.4	77.9
$L_{Use-II,OMF}$	51.8	51.8	53.4	55.2	56.4	57.2	57.8	58.4	58.9	59.3	59.7	60.1	60.4	60.8	61.2	61.5	61.9	62.2	62.6
In_{MP}	943.6	1046.4	1059.0	1073.1	1076.7	1073.7	1067.7	1060.5	1052.6	1044.4	1036.0	1027.6	1019.3	1011.1	1003.2	995.6	988.3	981.3	974.8
$Stock_{Use}$	873.0	903.6	935.2	967.9	1001.8	1036.9	1073.2	1110.7	1149.6	1189.8	1231.5	1274.6	1319.2	1365.4	1413.2	1462.6	1513.8	1566.8	1621.6
$\sum L_{Env}$	10.0	21.2	32.5	44.0	55.7	67.3	79.0	90.6	102.2	113.7	125.3	136.8	148.2	159.7	171.1	182.5	193.9	205.3	216.6
$\sum L_{OMF}$	524.5	1091.1	1669.7	2261.3	2859.8	3461.5	4064.5	4668.0	5271.4	5874.5	6476.9	7078.6	7679.5	8279.4	8878.5	9476.9	10074.5	10671.5	11268.0
$\sum L_{LF}$	409.1	847.2	1284.6	1721.9	2154.6	2579.9	2996.7	3404.6	3803.3	4192.8	4573.2	4944.6	5306.9	5660.4	6005.3	6341.7	6669.7	6989.7	7301.8

Table A 74: Results - TBC – F&M I variation - Optimistic- Min

F&M-I (spray powder production) variation (Optimistic) - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	378.8	409.5	406.6	403.7	408.5	406.2	416.0	426.3	424.3	422.4	420.6	418.8	417.1	415.5	414.0	412.6	411.2	409.9	408.6
$Out_{FM-I} = In_{Use}$	140.5	153.4	153.7	154.0	157.3	157.8	163.1	168.6	169.3	170.0	170.7	171.5	172.3	173.1	173.9	174.7	175.6	176.4	177.3
$Out_{MP} = In_{FM-I}$	378.8	409.5	406.6	403.7	408.5	406.2	416.0	426.3	424.3	422.4	420.6	418.8	417.1	415.5	414.0	412.6	411.2	409.9	408.6
$Out_{Use-II} = In_{EOL}$	68.2	68.2	68.2	68.2	69.6	69.7	72.1	74.6	74.7	74.9	75.0	75.2	75.4	75.6	75.8	76.0	76.1	76.3	76.5
$Out_{Use-I} = In_{Use-II}$	136.3	136.3	136.3	136.3	139.1	139.3	144.1	149.1	149.4	149.8	150.1	150.4	150.8	151.2	151.5	151.9	152.3	152.7	153.1
$L_{EOL,lf}$	6.8	6.8	6.8	6.8	7.0	7.0	7.2	7.5	7.5	7.5	7.5	7.5	7.5	7.6	7.6	7.6	7.6	7.6	7.7
$L_{EOL,omf}$	61.3	61.3	61.3	61.3	62.6	62.7	64.9	67.1	67.2	67.4	67.5	67.7	67.9	68.0	68.2	68.4	68.5	68.7	68.9
$L_{FM-I,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{FM-II,LF}$	23.8	25.6	25.3	25.0	25.1	24.8	25.3	25.8	25.5	25.2	25.0	24.7	24.5	24.2	24.0	23.8	23.6	23.3	23.1
$L_{FM-II,omf}$	214.5	230.5	227.6	224.7	226.1	223.5	227.6	231.9	229.5	227.1	224.8	222.6	220.4	218.2	216.1	214.1	212.0	210.1	208.2
$L_{MP,Env}$	1.6	1.7	1.6	1.6	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.3	1.3	1.2	1.2	1.1	1.1	1.1	1.0
$L_{MP,lf}$	144.2	152.9	148.9	144.9	143.8	140.1	140.7	141.2	137.7	134.3	130.9	127.6	124.4	121.3	118.2	115.2	112.3	109.4	106.6
$L_{MP,omf}$	1.6	1.7	1.6	1.6	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.3	1.3	1.2	1.2	1.1	1.1	1.1	1.0
$L_{Use-I,env}$	4.2	4.6	4.6	4.6	4.7	4.7	4.9	5.1	5.1	5.1	5.1	5.1	5.2	5.2	5.2	5.2	5.3	5.3	5.3
$L_{Use-II,lf}$	37.8	37.8	37.8	37.8	38.6	38.6	39.9	41.3	41.4	41.5	41.6	41.7	41.8	41.9	42.0	42.1	42.2	42.3	42.4
$L_{Use-II,OMF}$	30.4	30.4	30.4	30.4	31.0	31.0	32.1	33.2	33.3	33.4	33.4	33.5	33.6	33.7	33.8	33.8	33.9	34.0	34.1
In_{MP}	526.2	565.7	558.7	551.8	555.3	549.3	559.7	570.5	564.9	559.5	554.2	549.1	544.1	539.3	534.6	530.1	525.7	521.4	517.3
$Stock_{Use}$	497.5	510.0	522.7	535.8	549.2	562.9	577.0	591.4	606.2	621.3	636.9	652.8	669.1	685.8	703.0	720.6	738.6	757.0	776.0
$\sum L_{Env}$	5.8	12.1	18.3	24.5	30.7	37.0	43.3	49.9	56.4	62.9	69.4	75.8	82.3	88.7	95.1	101.5	107.9	114.2	120.6
$\sum L_{OMF}$	307.8	631.7	952.7	1270.7	1591.9	1910.7	2236.8	2570.5	2902.0	3231.3	3558.5	3883.6	4206.7	4527.8	4847.1	5164.5	5480.1	5794.0	6106.2
$\sum L_{LF}$	212.6	466.1	715.2	960.1	1205.5	1447.1	1692.3	1941.3	2186.7	2428.6	2667.1	2902.2	3134.0	3362.7	3588.2	3810.7	4030.3	4247.0	4460.9

Table A 75: Results - TBC – F&M I variation - Optimistic- Max

F&M-I (spray powder production) variation (Optimistic) - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	645.4	723.5	740.2	758.1	768.7	774.5	778.2	780.9	782.9	784.6	786.1	787.4	788.6	789.8	791.1	792.6	794.1	795.9	797.9
$Out_{FM-I} = In_{Use}$	239.5	271.0	279.8	289.2	295.9	300.9	305.1	308.8	312.4	315.8	319.1	322.4	325.7	329.0	332.3	335.6	339.1	342.6	346.3
$Out_{MP} = In_{FM-I}$	645.4	723.5	740.2	758.1	768.7	774.5	778.2	780.9	782.9	784.6	786.1	787.4	788.6	789.8	791.1	792.6	794.1	795.9	797.9
$Out_{Use-II} = In_{EOL}$	116.1	116.1	119.9	123.9	126.6	128.4	129.8	131.0	132.1	133.0	134.0	134.8	135.7	136.5	137.3	138.1	138.9	139.7	140.5
$Out_{Use-I} = In_{Use-II}$	232.3	232.3	239.8	247.8	253.2	256.8	259.6	262.0	264.1	266.1	267.9	269.7	271.3	272.9	274.5	276.1	277.7	279.4	281.1
$L_{EOL,lf}$	11.6	11.6	12.0	12.4	12.7	12.8	13.0	13.1	13.2	13.3	13.4	13.5	13.6	13.6	13.7	13.8	13.9	14.0	14.1
$L_{EOL,omf}$	104.5	104.5	107.9	111.5	113.9	115.6	116.8	117.9	118.9	119.7	120.6	121.3	122.1	122.8	123.5	124.3	125.0	125.7	126.5
$L_{FM-I,LF}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$L_{FM-II,LF}$	40.6	45.3	46.0	46.9	47.3	47.4	47.3	47.2	47.1	46.9	46.7	46.5	46.3	46.1	45.9	45.7	45.5	45.3	45.2
$L_{FM-II,omf}$	365.4	407.3	414.4	422.0	425.5	426.3	425.8	424.8	423.5	421.9	420.2	418.4	416.6	414.8	413.0	411.2	409.5	407.9	406.5
$L_{MP,Env}$	2.7	2.9	2.9	2.9	2.9	2.9	2.8	2.7	2.7	2.6	2.5	2.5	2.4	2.3	2.3	2.2	2.1	2.1	2.0
$L_{MP,lf}$	245.6	270.1	271.0	272.2	270.5	267.2	263.1	258.7	254.1	249.4	244.7	239.9	235.2	230.5	225.9	221.3	216.8	212.4	208.1
$L_{MP,omf}$	2.7	2.9	2.9	2.9	2.9	2.9	2.8	2.7	2.7	2.6	2.5	2.5	2.4	2.3	2.3	2.2	2.1	2.1	2.0
$L_{Use-I,env}$	7.2	8.1	8.4	8.7	8.9	9.0	9.2	9.3	9.4	9.5	9.6	9.7	9.8	9.9	10.0	10.1	10.2	10.3	10.4
$L_{Use-II,lf}$	64.4	64.4	66.5	68.7	70.2	71.2	72.0	72.6	73.2	73.8	74.3	74.7	75.2	75.7	76.1	76.5	77.0	77.4	77.9
$L_{Use-II,OMF}$	51.8	51.8	53.4	55.2	56.4	57.2	57.8	58.4	58.9	59.3	59.7	60.1	60.4	60.8	61.2	61.5	61.9	62.2	62.6
In_{MP}	896.5	999.5	1017.1	1036.1	1045.0	1047.5	1046.9	1045.0	1042.4	1039.2	1035.8	1032.2	1028.6	1025.0	1021.6	1018.3	1015.2	1012.5	1010.0
$Stock_{Use}$	873.0	903.6	935.2	967.9	1001.8	1036.9	1073.2	1110.7	1149.6	1189.8	1231.5	1274.6	1319.2	1365.4	1413.2	1462.6	1513.8	1566.8	1621.6
$\sum L_{Env}$	9.9	20.9	32.3	43.9	55.7	67.5	79.5	91.5	103.5	115.6	127.7	139.8	152.0	164.2	176.5	188.7	201.0	213.4	225.8
$\sum L_{OMF}$	524.4	1090.9	1669.5	2261.1	2859.8	3461.8	4065.1	4668.9	5272.8	5876.3	6479.3	7081.7	7683.2	8284.0	8883.9	9483.1	10081.6	10679.6	11277.2
$\sum L_{LF}$	362.2	753.6	1149.1	1549.2	1949.8	2348.5	2743.8	3135.5	3523.1	3906.4	4285.5	4660.1	5030.4	5396.3	5757.9	6115.2	6468.4	6817.5	7162.7

Table A 76: Results - TBC – F&M I variation - Pessimistic- Min

F&M-I (spray powder production) variation (Pessimistic) - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	378.8	409.5	406.6	403.7	408.5	406.2	416.0	426.3	424.3	422.4	420.6	418.8	417.1	415.5	414.0	412.6	411.2	409.9	408.6
$Out_{FM-I} = In_{Use}$	140.5	153.4	153.7	154.0	157.3	157.8	163.1	168.6	169.3	170.0	170.7	171.5	172.3	173.1	173.9	174.7	175.6	176.4	177.3
$Out_{MP} = In_{FM-I}$	420.9	455.0	451.8	448.6	453.8	451.3	462.3	473.6	471.4	469.3	467.3	465.3	463.5	461.7	460.0	458.4	456.9	455.4	454.0
$Out_{Use-II} = In_{EOL}$	68.2	68.2	68.2	68.2	69.6	69.7	72.1	74.6	74.7	74.9	75.0	75.2	75.4	75.6	75.8	76.0	76.1	76.3	76.5
$Out_{Use-I} = In_{Use-II}$	136.3	136.3	136.3	136.3	139.1	139.3	144.1	149.1	149.4	149.8	150.1	150.4	150.8	151.2	151.5	151.9	152.3	152.7	153.1
$L_{EOL,lf}$	6.8	6.8	6.8	6.8	7.0	7.0	7.2	7.5	7.5	7.5	7.5	7.5	7.5	7.6	7.6	7.6	7.6	7.6	7.7
$L_{EOL,omf}$	61.3	61.3	61.3	61.3	62.6	62.7	64.9	67.1	67.2	67.4	67.5	67.7	67.9	68.0	68.2	68.4	68.5	68.7	68.9
$L_{FM-I,LF}$	42.1	45.5	45.2	44.9	45.4	45.1	46.2	47.4	47.1	46.9	46.7	46.5	46.3	46.2	46.0	45.8	45.7	45.5	45.4
$L_{FM-II,LF}$	23.8	25.6	25.3	25.0	25.1	24.8	25.3	25.8	25.5	25.2	25.0	24.7	24.5	24.2	24.0	23.8	23.6	23.3	23.1
$L_{FM-II,omf}$	214.5	230.5	227.6	224.7	226.1	223.5	227.6	231.9	229.5	227.1	224.8	222.6	220.4	218.2	216.1	214.1	212.0	210.1	208.2
$L_{MP,Env}$	1.8	1.9	1.8	1.7	1.7	1.7	1.7	1.7	1.6	1.6	1.5	1.5	1.4	1.4	1.3	1.3	1.2	1.2	1.1
$L_{MP,lf}$	160.2	169.9	165.4	161.0	159.7	155.7	156.3	156.9	153.0	149.2	145.5	141.8	138.2	134.8	131.3	128.0	124.7	121.5	118.4
$L_{MP,omf}$	1.8	1.9	1.8	1.7	1.7	1.7	1.7	1.7	1.6	1.6	1.5	1.5	1.4	1.4	1.3	1.3	1.2	1.2	1.1
$L_{Use-I,env}$	4.2	4.6	4.6	4.6	4.7	4.7	4.9	5.1	5.1	5.1	5.1	5.1	5.2	5.2	5.2	5.2	5.3	5.3	5.3
$L_{Use-II,lf}$	37.8	37.8	37.8	37.8	38.6	38.6	39.9	41.3	41.4	41.5	41.6	41.7	41.8	41.9	42.0	42.1	42.2	42.3	42.4
$L_{Use-II,OMF}$	30.4	30.4	30.4	30.4	31.0	31.0	32.1	33.2	33.3	33.4	33.4	33.5	33.6	33.7	33.8	33.8	33.9	34.0	34.1
In_{MP}	584.6	628.6	620.8	613.1	617.0	610.3	621.9	633.9	627.7	621.6	615.8	610.1	604.5	599.2	594.0	588.9	584.1	579.3	574.7
$Stock_{Use}$	497.5	510.0	522.7	535.8	549.2	562.9	577.0	591.4	606.2	621.3	636.9	652.8	669.1	685.8	703.0	720.6	738.6	757.0	776.0
$\sum L_{Env}$	6.0	12.4	18.8	25.2	31.6	38.0	44.6	51.3	58.0	64.6	71.2	77.8	84.4	91.0	97.5	104.0	110.5	117.0	123.5
$\sum L_{OMF}$	307.9	632.1	953.2	1271.4	1592.8	1911.7	2238.0	2571.9	2903.5	3233.0	3560.3	3885.6	4208.8	4530.1	4849.5	5167.0	5482.7	5796.7	6109.0
$\sum L_{LF}$	270.7	586.7	897.5	1203.4	1510.2	1812.5	2119.5	2431.6	2739.4	3043.2	3342.9	3638.7	3930.7	4219.0	4503.7	4784.9	5062.6	5337.0	5608.1

Table A 77: Results - TBC – F&M I variation - Pessimistic- Max

F&M-I (spray powder production) variation (Pessimistic) - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	645.4	723.5	740.2	758.1	768.7	774.5	778.2	780.9	782.9	784.6	786.1	787.4	788.6	789.8	791.1	792.6	794.1	795.9	797.9
$Out_{FM-I} = In_{Use}$	239.5	271.0	279.8	289.2	295.9	300.9	305.1	308.8	312.4	315.8	319.1	322.4	325.7	329.0	332.3	335.6	339.1	342.6	346.3
$Out_{MP} = In_{FM-I}$	717.2	803.9	822.4	842.3	854.1	860.6	864.7	867.6	869.9	871.8	873.4	874.8	876.2	877.6	879.0	880.6	882.4	884.4	886.6
$Out_{Use-II} = In_{EOL}$	116.1	116.1	119.9	123.9	126.6	128.4	129.8	131.0	132.1	133.0	134.0	134.8	135.7	136.5	137.3	138.1	138.9	139.7	140.5
$Out_{Use-I} = In_{Use-II}$	232.3	232.3	239.8	247.8	253.2	256.8	259.6	262.0	264.1	266.1	267.9	269.7	271.3	272.9	274.5	276.1	277.7	279.4	281.1
$L_{EOL,lf}$	11.6	11.6	12.0	12.4	12.7	12.8	13.0	13.1	13.2	13.3	13.4	13.5	13.6	13.6	13.7	13.8	13.9	14.0	14.1
$L_{EOL,omf}$	104.5	104.5	107.9	111.5	113.9	115.6	116.8	117.9	118.9	119.7	120.6	121.3	122.1	122.8	123.5	124.3	125.0	125.7	126.5
$L_{FM-I,LF}$	71.7	80.4	82.2	84.2	85.4	86.1	86.5	86.8	87.0	87.2	87.3	87.5	87.6	87.8	87.9	88.1	88.2	88.4	88.7
$L_{FM-II,LF}$	40.6	45.3	46.0	46.9	47.3	47.4	47.3	47.2	47.1	46.9	46.7	46.5	46.3	46.1	45.9	45.7	45.5	45.3	45.2
$L_{FM-II,omf}$	365.4	407.3	414.4	422.0	425.5	426.3	425.8	424.8	423.5	421.9	420.2	418.4	416.6	414.8	413.0	411.2	409.5	407.9	406.5
$L_{MP,Env}$	3.0	3.3	3.3	3.3	3.2	3.2	3.1	3.0	3.0	2.9	2.8	2.7	2.7	2.6	2.5	2.5	2.4	2.3	2.2
$L_{MP,lf}$	272.9	300.1	301.1	302.4	300.6	296.9	292.4	287.4	282.3	277.1	271.9	266.6	261.3	256.1	251.0	245.9	240.9	236.0	231.2
$L_{MP,omf}$	3.0	3.3	3.3	3.3	3.2	3.2	3.1	3.0	3.0	2.9	2.8	2.7	2.7	2.6	2.5	2.5	2.4	2.3	2.2
$L_{Use-I,env}$	7.2	8.1	8.4	8.7	8.9	9.0	9.2	9.3	9.4	9.5	9.6	9.7	9.8	9.9	10.0	10.1	10.2	10.3	10.4
$L_{Use-II,lf}$	64.4	64.4	66.5	68.7	70.2	71.2	72.0	72.6	73.2	73.8	74.3	74.7	75.2	75.7	76.1	76.5	77.0	77.4	77.9
$L_{Use-II,OMF}$	51.8	51.8	53.4	55.2	56.4	57.2	57.8	58.4	58.9	59.3	59.7	60.1	60.4	60.8	61.2	61.5	61.9	62.2	62.6
In_{MP}	996.1	1110.6	1130.1	1151.2	1161.1	1163.9	1163.3	1161.1	1158.2	1154.7	1150.9	1146.9	1142.9	1138.9	1135.1	1131.4	1128.0	1125.0	1122.2
$Stock_{Use}$	873.0	903.6	935.2	967.9	1001.8	1036.9	1073.2	1110.7	1149.6	1189.8	1231.5	1274.6	1319.2	1365.4	1413.2	1462.6	1513.8	1566.8	1621.6
$\sum L_{Env}$	10.2	21.6	33.2	45.2	57.3	69.5	81.7	94.0	106.3	118.7	131.1	143.5	155.9	168.4	180.9	193.4	206.0	218.6	231.2
$\sum L_{OMF}$	524.7	1091.5	1670.4	2262.4	2861.5	3463.7	4067.3	4671.4	5275.6	5879.4	6482.7	7085.3	7687.2	8288.2	8888.3	9487.8	10086.6	10684.8	11282.6
$\sum L_{LF}$	461.2	963.0	1470.8	1985.4	2501.5	3015.9	3527.0	4034.1	4536.9	5035.2	5528.8	6017.6	6501.6	6980.9	7455.5	7925.5	8391.0	8852.1	9309.1

Table A 78: Results - TBC – F&M II variation - Optimistic- Min

F&M-II (coating) variation (Optimistic) - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	251.9	272.5	270.7	268.9	272.2	270.9	277.6	284.6	283.4	282.3	281.2	280.2	279.2	278.3	277.4	276.6	275.8	275.1	274.4
$Out_{FM-I} = In_{Use}$	140.5	153.4	153.7	154.0	157.3	157.8	163.1	168.6	169.3	170.0	170.7	171.5	172.3	173.1	173.9	174.7	175.6	176.4	177.3
$Out_{MP} = In_{FM-I}$	265.1	286.8	284.9	283.1	286.6	285.1	292.2	299.6	298.4	297.2	296.1	295.0	293.9	293.0	292.0	291.2	290.3	289.5	288.8
$Out_{Use-II} = In_{EOL}$	68.2	68.2	68.2	68.2	69.6	69.7	72.1	74.6	74.7	74.9	75.0	75.2	75.4	75.6	75.8	76.0	76.1	76.3	76.5
$Out_{Use-I} = In_{Use-II}$	136.3	136.3	136.3	136.3	139.1	139.3	144.1	149.1	149.4	149.8	150.1	150.4	150.8	151.2	151.5	151.9	152.3	152.7	153.1
$L_{EOL,lf}$	6.8	6.8	6.8	6.8	7.0	7.0	7.2	7.5	7.5	7.5	7.5	7.5	7.5	7.6	7.6	7.6	7.6	7.6	7.7
$L_{EOL,omf}$	61.3	61.3	61.3	61.3	62.6	62.7	64.9	67.1	67.2	67.4	67.5	67.7	67.9	68.0	68.2	68.4	68.5	68.7	68.9
$L_{FM-I,LF}$	13.3	14.3	14.2	14.2	14.3	14.3	14.6	15.0	14.9	14.9	14.8	14.7	14.7	14.6	14.6	14.6	14.5	14.5	14.4
$L_{FM-II,LF}$	11.1	11.9	11.7	11.5	11.5	11.3	11.5	11.6	11.4	11.2	11.0	10.9	10.7	10.5	10.4	10.2	10.0	9.9	9.7
$L_{FM-II,omf}$	100.2	107.2	105.3	103.4	103.5	101.8	103.1	104.4	102.7	101.1	99.4	97.8	96.3	94.7	93.2	91.7	90.2	88.8	87.3
$L_{MP,Env}$	1.1	1.2	1.1	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.7
$L_{MP,lf}$	100.9	107.1	104.3	101.6	100.9	98.4	98.8	99.3	96.8	94.5	92.2	89.9	87.7	85.5	83.4	81.3	79.3	77.3	75.3
$L_{MP,omf}$	1.1	1.2	1.1	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.7
$L_{Use-I,env}$	4.2	4.6	4.6	4.6	4.7	4.7	4.9	5.1	5.1	5.1	5.1	5.1	5.2	5.2	5.2	5.2	5.3	5.3	5.3
$L_{Use-II,lf}$	37.8	37.8	37.8	37.8	38.6	38.6	39.9	41.3	41.4	41.5	41.6	41.7	41.8	41.9	42.0	42.1	42.2	42.3	42.4
$L_{Use-II,OMF}$	30.4	30.4	30.4	30.4	31.0	31.0	32.1	33.2	33.3	33.4	33.4	33.5	33.6	33.7	33.8	33.8	33.9	34.0	34.1
In_{MP}	368.2	396.2	391.5	386.9	389.6	385.6	393.1	400.9	397.2	393.6	390.1	386.7	383.4	380.2	377.1	374.1	371.2	368.3	365.6
$Stock_{Use}$	497.5	510.0	522.7	535.8	549.2	562.9	577.0	591.4	606.2	621.3	636.9	652.8	669.1	685.8	703.0	720.6	738.6	757.0	776.0
$\sum L_{Env}$	5.3	11.1	16.8	22.5	28.3	34.1	40.1	46.2	52.3	58.4	64.4	70.5	76.6	82.6	88.7	94.7	100.8	106.8	112.9
$\sum L_{OMF}$	193.0	393.1	591.2	787.5	985.6	1182.2	1383.3	1589.1	1793.3	1996.2	2197.6	2397.5	2596.2	2793.4	2989.4	3184.1	3377.6	3569.8	3760.9
$\sum L_{LF}$	169.9	378.2	583.4	785.7	988.9	1189.5	1393.6	1601.4	1806.8	2009.7	2210.3	2408.5	2604.5	2798.3	2990.0	3179.6	3367.2	3552.7	3736.4

Table A 79: Results - TBC – F&M II variation - Optimistic - Max

F&M-II (coating) variation (Optimistic) - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	429.1	481.4	492.7	505.0	512.3	516.5	519.3	521.3	523.0	524.4	525.7	526.8	527.9	529.0	530.2	531.4	532.7	534.1	535.7
$Out_{FM-I} = In_{Use}$	239.5	271.0	279.8	289.2	295.9	300.9	305.1	308.8	312.4	315.8	319.1	322.4	325.7	329.0	332.3	335.6	339.1	342.6	346.3
$Out_{MP} = In_{FM-I}$	451.7	506.7	518.7	531.5	539.3	543.7	546.6	548.8	550.5	552.0	553.3	554.5	555.7	556.9	558.1	559.3	560.7	562.2	563.9
$Out_{Use-II} = In_{EOL}$	116.1	116.1	119.9	123.9	126.6	128.4	129.8	131.0	132.1	133.0	134.0	134.8	135.7	136.5	137.3	138.1	138.9	139.7	140.5
$Out_{Use-I} = In_{Use-II}$	232.3	232.3	239.8	247.8	253.2	256.8	259.6	262.0	264.1	266.1	267.9	269.7	271.3	272.9	274.5	276.1	277.7	279.4	281.1
$L_{EOL,lf}$	11.6	11.6	12.0	12.4	12.7	12.8	13.0	13.1	13.2	13.3	13.4	13.5	13.6	13.6	13.7	13.8	13.9	14.0	14.1
$L_{EOL,omf}$	104.5	104.5	107.9	111.5	113.9	115.6	116.8	117.9	118.9	119.7	120.6	121.3	122.1	122.8	123.5	124.3	125.0	125.7	126.5
$L_{FM-I,LF}$	22.6	25.3	25.9	26.6	27.0	27.2	27.3	27.4	27.5	27.6	27.7	27.7	27.8	27.8	27.9	28.0	28.0	28.1	28.2
$L_{FM-II,LF}$	19.0	21.0	21.3	21.6	21.6	21.6	21.4	21.3	21.1	20.9	20.7	20.4	20.2	20.0	19.8	19.6	19.4	19.1	18.9
$L_{FM-II,omf}$	170.7	189.4	191.7	194.2	194.7	194.1	192.8	191.3	189.6	187.8	185.9	184.0	182.0	180.0	178.1	176.1	174.2	172.3	170.5
$L_{MP,Env}$	1.9	2.1	2.1	2.1	2.0	2.0	2.0	1.9	1.9	1.8	1.8	1.7	1.7	1.6	1.6	1.6	1.5	1.5	1.4
$L_{MP,lf}$	171.9	189.1	189.9	190.8	189.8	187.6	184.8	181.8	178.7	175.5	172.2	169.0	165.7	162.5	159.3	156.2	153.1	150.0	147.0
$L_{MP,omf}$	1.9	2.1	2.1	2.1	2.0	2.0	2.0	1.9	1.9	1.8	1.8	1.7	1.7	1.6	1.6	1.6	1.5	1.5	1.4
$L_{Use-I,env}$	7.2	8.1	8.4	8.7	8.9	9.0	9.2	9.3	9.4	9.5	9.6	9.7	9.8	9.9	10.0	10.1	10.2	10.3	10.4
$L_{Use-II,lf}$	64.4	64.4	66.5	68.7	70.2	71.2	72.0	72.6	73.2	73.8	74.3	74.7	75.2	75.7	76.1	76.5	77.0	77.4	77.9
$L_{Use-II,OMF}$	51.8	51.8	53.4	55.2	56.4	57.2	57.8	58.4	58.9	59.3	59.7	60.1	60.4	60.8	61.2	61.5	61.9	62.2	62.6
In_{MP}	627.4	700.0	712.7	726.5	733.2	735.3	735.4	734.4	733.0	731.2	729.1	727.0	724.8	722.7	720.6	718.6	716.8	715.2	713.8
$Stock_{Use}$	873.0	903.6	935.2	967.9	1001.8	1036.9	1073.2	1110.7	1149.6	1189.8	1231.5	1274.6	1319.2	1365.4	1413.2	1462.6	1513.8	1566.8	1621.6
$\sum L_{Env}$	9.1	19.3	29.7	40.4	51.4	62.4	73.5	84.7	95.9	107.2	118.6	130.0	141.5	153.0	164.5	176.2	187.9	199.6	211.4
$\sum L_{OMF}$	328.9	676.6	1031.6	1394.6	1761.7	2130.5	2500.0	2869.4	3238.6	3607.2	3975.1	4342.2	4708.4	5073.8	5438.1	5801.6	6164.2	6526.0	6887.0
$\sum L_{LF}$	289.5	601.0	916.6	1236.6	1557.9	1878.2	2196.8	2513.0	2826.7	3137.7	3445.9	3751.3	4053.8	4353.5	4650.3	4944.4	5235.8	5524.5	5810.6

Table A 80: Results - TBC – F&M II variation - Pessimistic - Min

F&M-II (coating) variation (Pessimistic) - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	763.9	833.5	835.3	837.1	854.6	857.6	886.3	916.3	920.1	924.0	928.0	932.1	936.3	940.6	945.0	949.6	954.2	959.0	963.8
$Out_{FM-I} = In_{Use}$	140.5	153.4	153.7	154.0	157.3	157.8	163.1	168.6	169.3	170.0	170.7	171.5	172.3	173.1	173.9	174.7	175.6	176.4	177.3
$Out_{MP} = In_{FM-I}$	804.1	877.4	879.2	881.1	899.6	902.7	933.0	964.5	968.5	972.6	976.8	981.1	985.6	990.1	994.8	999.5	1004.4	1009.4	1014.6
$Out_{Use-II} = In_{EOL}$	68.2	68.2	68.2	68.2	69.6	69.7	72.1	74.6	74.7	74.9	75.0	75.2	75.4	75.6	75.8	76.0	76.1	76.3	76.5
$Out_{Use-I} = In_{Use-II}$	136.3	136.3	136.3	136.3	139.1	139.3	144.1	149.1	149.4	149.8	150.1	150.4	150.8	151.2	151.5	151.9	152.3	152.7	153.1
$L_{EOL,lf}$	6.8	6.8	6.8	6.8	7.0	7.0	7.2	7.5	7.5	7.5	7.5	7.5	7.5	7.6	7.6	7.6	7.6	7.6	7.7
$L_{EOL,omf}$	61.3	61.3	61.3	61.3	62.6	62.7	64.9	67.1	67.2	67.4	67.5	67.7	67.9	68.0	68.2	68.4	68.5	68.7	68.9
$L_{FM-I,LF}$	40.2	43.9	44.0	44.1	45.0	45.1	46.6	48.2	48.4	48.6	48.8	49.1	49.3	49.5	49.7	50.0	50.2	50.5	50.7
$L_{FM-II,LF}$	62.3	68.0	68.2	68.3	69.7	70.0	72.3	74.8	75.1	75.4	75.7	76.1	76.4	76.8	77.1	77.5	77.9	78.3	78.6
$L_{FM-II,omf}$	561.0	612.2	613.4	614.7	627.7	629.8	650.9	672.9	675.7	678.6	681.5	684.5	687.6	690.8	694.0	697.4	700.8	704.3	707.8
$L_{MP,Env}$	3.4	3.6	3.5	3.4	3.4	3.3	3.3	3.4	3.3	3.2	3.1	3.1	3.0	2.9	2.9	2.8	2.7	2.6	2.6
$L_{MP,lf}$	306.0	327.5	321.9	316.3	316.6	311.5	315.5	319.5	314.3	309.2	304.1	299.0	294.0	289.0	284.0	279.1	274.2	269.4	264.6
$L_{MP,omf}$	3.4	3.6	3.5	3.4	3.4	3.3	3.3	3.4	3.3	3.2	3.1	3.1	3.0	2.9	2.9	2.8	2.7	2.6	2.6
$L_{Use-I,env}$	4.2	4.6	4.6	4.6	4.7	4.7	4.9	5.1	5.1	5.1	5.1	5.1	5.2	5.2	5.2	5.2	5.3	5.3	5.3
$L_{Use-II,lf}$	37.8	37.8	37.8	37.8	38.6	38.6	39.9	41.3	41.4	41.5	41.6	41.7	41.8	41.9	42.0	42.1	42.2	42.3	42.4
$L_{Use-II,OMF}$	30.4	30.4	30.4	30.4	31.0	31.0	32.1	33.2	33.3	33.4	33.4	33.5	33.6	33.7	33.8	33.8	33.9	34.0	34.1
In_{MP}	1116.7	1212.1	1208.1	1204.3	1223.1	1220.8	1255.1	1290.8	1289.4	1288.2	1287.2	1286.3	1285.5	1284.9	1284.5	1284.2	1284.1	1284.1	1284.3
$Stock_{Use}$	497.5	510.0	522.7	535.8	549.2	562.9	577.0	591.4	606.2	621.3	636.9	652.8	669.1	685.8	703.0	720.6	738.6	757.0	776.0
$\sum L_{Env}$	7.6	15.7	23.8	31.9	40.0	48.0	56.3	64.7	73.1	81.4	89.7	97.9	106.1	114.2	122.2	130.3	138.3	146.2	154.1
$\sum L_{OMF}$	656.0	1363.5	2072.1	2782.0	3506.7	4233.6	4984.8	5761.4	6540.9	7323.5	8109.1	8897.9	9690.0	10485.4	11284.2	12086.6	12892.5	13702.1	14515.5
$\sum L_{LF}$	453.1	967.5	1476.5	1980.2	2488.1	2991.3	3505.0	4029.5	4549.5	5065.1	5576.3	6083.1	6585.7	7084.1	7578.3	8068.4	8554.4	9036.5	9514.6

Table A 81: Results - TBC – F&M II variation - Pessimistic - Max

F&M-II (coating) variation (Pessimistic) - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	1301.4	1472.6	1520.6	1571.8	1608.4	1635.4	1657.9	1678.4	1697.8	1716.4	1734.5	1752.3	1770.1	1787.9	1805.9	1824.2	1842.9	1862.2	1882.0
$Out_{FM-I} = In_{Use}$	239.5	271.0	279.8	289.2	295.9	300.9	305.1	308.8	312.4	315.8	319.1	322.4	325.7	329.0	332.3	335.6	339.1	342.6	346.3
$Out_{MP} = In_{FM-I}$	1369.9	1550.1	1600.6	1654.5	1693.0	1721.5	1745.2	1766.8	1787.1	1806.7	1825.8	1844.5	1863.2	1881.9	1900.9	1920.2	1939.9	1960.2	1981.1
$Out_{Use-II} = In_{EOL}$	116.1	116.1	119.9	123.9	126.6	128.4	129.8	131.0	132.1	133.0	134.0	134.8	135.7	136.5	137.3	138.1	138.9	139.7	140.5
$Out_{Use-I} = In_{Use-II}$	232.3	232.3	239.8	247.8	253.2	256.8	259.6	262.0	264.1	266.1	267.9	269.7	271.3	272.9	274.5	276.1	277.7	279.4	281.1
$L_{EOL,lf}$	11.6	11.6	12.0	12.4	12.7	12.8	13.0	13.1	13.2	13.3	13.4	13.5	13.6	13.6	13.7	13.8	13.9	14.0	14.1
$L_{EOL,omf}$	104.5	104.5	107.9	111.5	113.9	115.6	116.8	117.9	118.9	119.7	120.6	121.3	122.1	122.8	123.5	124.3	125.0	125.7	126.5
$L_{FM-I,LF}$	68.5	77.5	80.0	82.7	84.7	86.1	87.3	88.3	89.4	90.3	91.3	92.2	93.2	94.1	95.0	96.0	97.0	98.0	99.1
$L_{FM-II,LF}$	106.2	120.2	124.1	128.3	131.2	133.4	135.3	137.0	138.5	140.1	141.5	143.0	144.4	145.9	147.4	148.9	150.4	152.0	153.6
$L_{FM-II,omf}$	955.8	1081.5	1116.7	1154.3	1181.2	1201.0	1217.6	1232.6	1246.8	1260.5	1273.8	1286.9	1299.9	1313.0	1326.2	1339.7	1353.5	1367.6	1382.1
$L_{MP,Env}$	5.7	6.3	6.4	6.4	6.4	6.3	6.3	6.2	6.1	6.0	5.9	5.8	5.7	5.6	5.5	5.3	5.2	5.1	5.0
$L_{MP,lf}$	521.3	578.6	586.0	594.0	595.9	593.9	590.1	585.3	580.0	574.3	568.3	562.1	555.7	549.3	542.7	536.2	529.6	523.1	516.6
$L_{MP,omf}$	5.7	6.3	6.4	6.4	6.4	6.3	6.3	6.2	6.1	6.0	5.9	5.8	5.7	5.6	5.5	5.3	5.2	5.1	5.0
$L_{Use-I,env}$	7.2	8.1	8.4	8.7	8.9	9.0	9.2	9.3	9.4	9.5	9.6	9.7	9.8	9.9	10.0	10.1	10.2	10.3	10.4
$L_{Use-II,lf}$	64.4	64.4	66.5	68.7	70.2	71.2	72.0	72.6	73.2	73.8	74.3	74.7	75.2	75.7	76.1	76.5	77.0	77.4	77.9
$L_{Use-II,OMF}$	51.8	51.8	53.4	55.2	56.4	57.2	57.8	58.4	58.9	59.3	59.7	60.1	60.4	60.8	61.2	61.5	61.9	62.2	62.6
In_{MP}	1902.7	2141.4	2199.3	2261.3	2301.7	2328.1	2347.8	2364.4	2379.3	2393.0	2405.8	2418.2	2430.3	2442.3	2454.5	2467.1	2480.0	2493.5	2507.7
$Stock_{Use}$	873.0	903.6	935.2	967.9	1001.8	1036.9	1073.2	1110.7	1149.6	1189.8	1231.5	1274.6	1319.2	1365.4	1413.2	1462.6	1513.8	1566.8	1621.6
$\sum L_{Env}$	12.9	27.3	42.1	57.2	72.4	87.8	103.2	118.6	134.1	149.6	165.0	180.5	195.9	211.3	226.8	242.2	257.6	273.0	288.4
$\sum L_{OMF}$	1117.7	2361.8	3646.2	4973.7	6331.6	7711.8	9110.3	10525.4	11956.0	13401.5	14861.4	16335.5	17823.6	19325.8	20842.2	22373.0	23918.6	25479.2	27055.5
$\sum L_{LF}$	772.0	1624.3	2492.9	3378.9	4273.6	5171.0	6068.6	6965.0	7859.3	8751.1	9639.9	10525.4	11407.5	12286.0	13161.0	14032.4	14900.2	15764.7	16625.9

Table A 82: Results - TBC – In-use dissipation variation - High - Min

In-use dissipation variation (high) - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	378.8	409.5	406.6	403.7	408.5	406.2	416.0	426.3	424.3	422.4	420.6	418.8	417.1	415.5	414.0	412.6	411.2	409.9	408.6
$Out_{FM-I} = In_{Use}$	140.5	153.4	153.7	154.0	157.3	157.8	163.1	168.6	169.3	170.0	170.7	171.5	172.3	173.1	173.9	174.7	175.6	176.4	177.3
$Out_{MP} = In_{FM-I}$	398.8	431.1	428.0	425.0	430.0	427.6	437.9	448.7	446.6	444.6	442.7	440.9	439.1	437.4	435.8	434.3	432.8	431.4	430.1
$Out_{Use-II} = In_{EOL}$	63.2	63.2	63.2	63.2	64.6	64.6	66.9	69.2	69.3	69.5	69.6	69.8	70.0	70.1	70.3	70.5	70.7	70.8	71.0
$Out_{Use-I} = In_{Use-II}$	126.5	126.5	126.5	126.5	129.1	129.3	133.7	138.4	138.6	139.0	139.3	139.6	139.9	140.2	140.6	140.9	141.3	141.7	142.1
$L_{EOL,lf}$	6.3	6.3	6.3	6.3	6.5	6.5	6.7	6.9	6.9	6.9	7.0	7.0	7.0	7.0	7.0	7.0	7.1	7.1	7.1
$L_{EOL,omf}$	56.9	56.9	56.9	56.9	58.1	58.2	60.2	62.3	62.4	62.5	62.7	62.8	63.0	63.1	63.3	63.4	63.6	63.8	63.9
$L_{FM-I,LF}$	19.9	21.6	21.4	21.2	21.5	21.4	21.9	22.4	22.3	22.2	22.1	22.0	22.0	21.9	21.8	21.7	21.6	21.6	21.5
$L_{FM-II,LF}$	23.8	25.6	25.3	25.0	25.1	24.8	25.3	25.8	25.5	25.2	25.0	24.7	24.5	24.2	24.0	23.8	23.6	23.3	23.1
$L_{FM-II,omf}$	214.5	230.5	227.6	224.7	226.1	223.5	227.6	231.9	229.5	227.1	224.8	222.6	220.4	218.2	216.1	214.1	212.0	210.1	208.2
$L_{MP,Env}$	1.7	1.8	1.7	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.1	1.1
$L_{MP,lf}$	151.8	160.9	156.7	152.6	151.3	147.5	148.1	148.7	145.0	141.3	137.8	134.3	131.0	127.7	124.4	121.3	118.2	115.1	112.2
$L_{MP,omf}$	1.7	1.8	1.7	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.1	1.1
$L_{Use-I,env}$	14.1	15.3	15.4	15.4	15.7	15.8	16.3	16.9	16.9	17.0	17.1	17.2	17.2	17.3	17.4	17.5	17.6	17.6	17.7
$L_{Use-II,lf}$	35.1	35.1	35.1	35.1	35.8	35.8	37.1	38.4	38.4	38.5	38.6	38.7	38.8	38.9	39.0	39.1	39.2	39.3	39.4
$L_{Use-II,OMF}$	28.2	28.2	28.2	28.2	28.8	28.8	29.8	30.8	30.9	31.0	31.0	31.1	31.2	31.2	31.3	31.4	31.5	31.6	31.6
In_{MP}	553.9	595.5	588.1	580.8	584.5	578.2	589.1	600.5	594.6	588.9	583.4	578.0	572.7	567.7	562.7	557.9	553.3	548.8	544.5
$Stock_{Use}$	461.6	473.2	485.0	497.1	509.5	522.3	535.3	548.7	562.4	576.5	590.9	605.7	620.8	636.3	652.3	668.6	685.3	702.4	720.0
$\sum L_{Env}$	15.7	32.8	49.9	66.9	84.3	101.6	119.5	137.9	156.4	174.9	193.4	211.9	230.5	249.1	267.7	286.4	305.1	323.9	342.7
$\sum L_{OMF}$	301.2	618.6	933.1	1244.5	1559.1	1871.2	2190.4	2516.9	2841.2	3163.3	3483.3	3801.2	4117.0	4430.9	4742.8	5052.9	5361.2	5667.7	5972.5
$\sum L_{LF}$	236.9	514.6	787.5	1055.9	1324.8	1589.7	1858.5	2131.4	2400.5	2665.7	2927.2	3185.1	3439.5	3690.4	3937.9	4182.2	4423.3	4661.2	4896.2

Table A 83: Results - TBC – In-use dissipation variation - High - Max

In-use dissipation variation (high) - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	645.4	723.5	740.2	758.1	768.7	774.5	778.2	780.9	782.9	784.6	786.1	787.4	788.6	789.8	791.1	792.6	794.1	795.9	797.9
$Out_{FM-I} = In_{Use}$	239.5	271.0	279.8	289.2	295.9	300.9	305.1	308.8	312.4	315.8	319.1	322.4	325.7	329.0	332.3	335.6	339.1	342.6	346.3
$Out_{MP} = In_{FM-I}$	679.4	761.6	779.1	798.0	809.1	815.3	819.2	822.0	824.1	825.9	827.4	828.8	830.1	831.4	832.8	834.3	835.9	837.8	839.9
$Out_{Use-II} = In_{EOL}$	107.8	107.8	111.2	115.0	117.5	119.1	120.4	121.5	122.5	123.4	124.3	125.1	125.9	126.6	127.4	128.1	128.8	129.6	130.4
$Out_{Use-I} = In_{Use-II}$	215.5	215.5	222.5	229.9	234.9	238.3	240.9	243.1	245.1	246.9	248.6	250.2	251.7	253.2	254.7	256.2	257.7	259.2	260.8
$L_{EOL,lf}$	10.8	10.8	11.1	11.5	11.7	11.9	12.0	12.2	12.3	12.3	12.4	12.5	12.6	12.7	12.7	12.8	12.9	13.0	13.0
$L_{EOL,omf}$	97.0	97.0	100.1	103.5	105.7	107.2	108.4	109.4	110.3	111.1	111.9	112.6	113.3	114.0	114.6	115.3	116.0	116.6	117.4
$L_{FM-I,LF}$	34.0	38.1	39.0	39.9	40.5	40.8	41.0	41.1	41.2	41.3	41.4	41.4	41.5	41.6	41.6	41.7	41.8	41.9	42.0
$L_{FM-II,LF}$	40.6	45.3	46.0	46.9	47.3	47.4	47.3	47.2	47.1	46.9	46.7	46.5	46.3	46.1	45.9	45.7	45.5	45.3	45.2
$L_{FM-II,omf}$	365.4	407.3	414.4	422.0	425.5	426.3	425.8	424.8	423.5	421.9	420.2	418.4	416.6	414.8	413.0	411.2	409.5	407.9	406.5
$L_{MP,Env}$	2.8	3.1	3.1	3.1	3.1	3.0	2.9	2.9	2.8	2.7	2.7	2.6	2.5	2.5	2.4	2.3	2.3	2.2	2.1
$L_{MP,lf}$	258.6	284.3	285.3	286.5	284.8	281.3	277.0	272.3	267.5	262.5	257.6	252.6	247.6	242.6	237.8	233.0	228.2	223.6	219.0
$L_{MP,omf}$	2.8	3.1	3.1	3.1	3.1	3.0	2.9	2.9	2.8	2.7	2.7	2.6	2.5	2.5	2.4	2.3	2.3	2.2	2.1
$L_{Use-I,env}$	23.9	27.1	28.0	28.9	29.6	30.1	30.5	30.9	31.2	31.6	31.9	32.2	32.6	32.9	33.2	33.6	33.9	34.3	34.6
$L_{Use-II,lf}$	59.7	59.7	61.7	63.7	65.1	66.1	66.8	67.4	67.9	68.4	68.9	69.4	69.8	70.2	70.6	71.0	71.4	71.9	72.3
$L_{Use-II,OMF}$	48.0	48.0	49.6	51.2	52.3	53.1	53.7	54.2	54.6	55.0	55.4	55.7	56.1	56.4	56.7	57.1	57.4	57.8	58.1
In_{MP}	943.6	1052.1	1070.6	1090.6	1100.0	1102.6	1102.0	1100.0	1097.2	1093.9	1090.3	1086.6	1082.7	1079.0	1075.3	1071.9	1068.7	1065.8	1063.2
$Stock_{Use}$	810.0	838.4	867.7	898.1	929.5	962.0	995.7	1030.6	1066.6	1104.0	1142.6	1182.6	1224.0	1266.8	1311.2	1357.1	1404.6	1453.7	1504.6
$\sum L_{Env}$	26.8	57.0	88.0	120.1	152.7	185.8	219.2	253.0	287.0	321.4	355.9	390.8	425.9	461.2	496.8	532.7	568.9	605.3	642.1
$\sum L_{OMF}$	513.2	1068.6	1635.7	2215.5	2802.1	3391.7	3982.5	4573.8	5165.0	5755.7	6345.9	6935.2	7523.7	8111.4	8698.1	9284.0	9869.2	10453.7	11037.7
$\sum L_{LF}$	403.6	841.8	1284.8	1733.3	2182.7	2630.1	3074.2	3514.3	3950.2	4381.7	4808.7	5231.1	5648.8	6062.0	6470.6	6874.8	7274.6	7670.2	8061.7

Table A 84: Results - TBC – Use phase maintenance variation – Scenario B - Min

Use phase Maintenance variation (Scenario B) - Min – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	378.8	409.5	406.6	403.7	408.5	406.2	416.0	426.3	424.3	422.4	420.6	418.8	417.1	415.5	414.0	412.6	411.2	409.9	408.6
$Out_{FM-I} = In_{Use}$	140.5	153.4	153.7	154.0	157.3	157.8	163.1	168.6	169.3	170.0	170.7	171.5	172.3	173.1	173.9	174.7	175.6	176.4	177.3
$Out_{MP} = In_{FM-I}$	398.8	431.1	428.0	425.0	430.0	427.6	437.9	448.7	446.6	444.6	442.7	440.9	439.1	437.4	435.8	434.3	432.8	431.4	430.1
$Out_{Use-II} = In_{EOL}$	68.2	68.2	68.2	68.2	69.6	69.7	72.1	74.6	74.7	74.9	75.0	75.2	75.4	75.6	75.8	76.0	76.1	76.3	76.5
$Out_{Use-I} = In_{Use-II}$	136.3	136.3	136.3	136.3	139.1	139.3	144.1	149.1	149.4	149.8	150.1	150.4	150.8	151.2	151.5	151.9	152.3	152.7	153.1
$L_{EOL,lf}$	6.8	6.8	6.8	6.8	7.0	7.0	7.2	7.5	7.5	7.5	7.5	7.5	7.5	7.6	7.6	7.6	7.6	7.6	7.7
$L_{EOL,omf}$	61.3	61.3	61.3	61.3	62.6	62.7	64.9	67.1	67.2	67.4	67.5	67.7	67.9	68.0	68.2	68.4	68.5	68.7	68.9
$L_{FM-I,LF}$	19.9	21.6	21.4	21.2	21.5	21.4	21.9	22.4	22.3	22.2	22.1	22.0	22.0	21.9	21.8	21.7	21.6	21.6	21.5
$L_{FM-II,LF}$	23.8	25.6	25.3	25.0	25.1	24.8	25.3	25.8	25.5	25.2	25.0	24.7	24.5	24.2	24.0	23.8	23.6	23.3	23.1
$L_{FM-II,omf}$	214.5	230.5	227.6	224.7	226.1	223.5	227.6	231.9	229.5	227.1	224.8	222.6	220.4	218.2	216.1	214.1	212.0	210.1	208.2
$L_{MP,Env}$	1.7	1.8	1.7	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.1	1.1
$L_{MP,lf}$	151.8	160.9	156.7	152.6	151.3	147.5	148.1	148.7	145.0	141.3	137.8	134.3	131.0	127.7	124.4	121.3	118.2	115.1	112.2
$L_{MP,omf}$	1.7	1.8	1.7	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.1	1.1
$L_{Use-I,env}$	4.2	4.6	4.6	4.6	4.7	4.7	4.9	5.1	5.1	5.1	5.1	5.1	5.2	5.2	5.2	5.2	5.3	5.3	5.3
$L_{Use-II,lf}$	33.9	33.9	33.9	33.9	34.6	34.6	35.8	37.0	37.1	37.2	37.3	37.4	37.5	37.6	37.6	37.7	37.8	37.9	38.0
$L_{Use-II,OMF}$	34.3	34.3	34.3	34.3	35.0	35.1	36.3	37.5	37.6	37.7	37.8	37.8	37.9	38.0	38.1	38.2	38.3	38.4	38.5
In_{MP}	553.9	595.5	588.1	580.8	584.5	578.2	589.1	600.5	594.6	588.9	583.4	578.0	572.7	567.7	562.7	557.9	553.3	548.8	544.5
$Stock_{Use}$	497.5	510.0	522.7	535.8	549.2	562.9	577.0	591.4	606.2	621.3	636.9	652.8	669.1	685.8	703.0	720.6	738.6	757.0	776.0
$\sum L_{Env}$	5.9	12.2	18.5	24.8	31.1	37.5	43.9	50.5	57.1	63.7	70.3	76.8	83.3	89.8	96.2	102.7	109.1	115.6	122.0
$\sum L_{OMF}$	311.8	639.7	964.7	1286.7	1612.0	1934.9	2265.2	2603.3	2939.1	3272.8	3604.4	3933.9	4261.4	4586.9	4910.6	5232.4	5552.5	5870.8	6187.5
$\sum L_{LF}$	236.2	519.3	797.7	1071.4	1345.9	1616.3	1890.8	2169.7	2444.6	2715.8	2983.3	3247.1	3507.5	3764.4	4017.9	4268.2	4515.4	4759.4	5000.4

Table A 85: Results - TBC – Use phase maintenance variation – Scenario B - Max

Use phase Maintenance variation (Scenario B) - Max – Stocks and Flows in kilograms																			
Parameter	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
$Out_{FM-I} = In_{FM-II}$	645.4	723.5	740.2	758.1	768.7	774.5	778.2	780.9	782.9	784.6	786.1	787.4	788.6	789.8	791.1	792.6	794.1	795.9	797.9
$Out_{FM-I} = In_{Use}$	239.5	271.0	279.8	289.2	295.9	300.9	305.1	308.8	312.4	315.8	319.1	322.4	325.7	329.0	332.3	335.6	339.1	342.6	346.3
$Out_{MP} = In_{FM-I}$	679.4	761.6	779.1	798.0	809.1	815.3	819.2	822.0	824.1	825.9	827.4	828.8	830.1	831.4	832.8	834.3	835.9	837.8	839.9
$Out_{Use-II} = In_{EOL}$	116.1	116.1	119.9	123.9	126.6	128.4	129.8	131.0	132.1	133.0	134.0	134.8	135.7	136.5	137.3	138.1	138.9	139.7	140.5
$Out_{Use-I} = In_{Use-II}$	232.3	232.3	239.8	247.8	253.2	256.8	259.6	262.0	264.1	266.1	267.9	269.7	271.3	272.9	274.5	276.1	277.7	279.4	281.1
$L_{EOL,lf}$	11.6	11.6	12.0	12.4	12.7	12.8	13.0	13.1	13.2	13.3	13.4	13.5	13.6	13.6	13.7	13.8	13.9	14.0	14.1
$L_{EOL,omf}$	104.5	104.5	107.9	111.5	113.9	115.6	116.8	117.9	118.9	119.7	120.6	121.3	122.1	122.8	123.5	124.3	125.0	125.7	126.5
$L_{FM-I,LF}$	34.0	38.1	39.0	39.9	40.5	40.8	41.0	41.1	41.2	41.3	41.4	41.4	41.5	41.6	41.6	41.7	41.8	41.9	42.0
$L_{FM-II,LF}$	40.6	45.3	46.0	46.9	47.3	47.4	47.3	47.2	47.1	46.9	46.7	46.5	46.3	46.1	45.9	45.7	45.5	45.3	45.2
$L_{FM-II,omf}$	365.4	407.3	414.4	422.0	425.5	426.3	425.8	424.8	423.5	421.9	420.2	418.4	416.6	414.8	413.0	411.2	409.5	407.9	406.5
$L_{MP,Env}$	2.8	3.1	3.1	3.1	3.1	3.0	2.9	2.9	2.8	2.7	2.7	2.6	2.5	2.5	2.4	2.3	2.3	2.2	2.1
$L_{MP,lf}$	258.6	284.3	285.3	286.5	284.8	281.3	277.0	272.3	267.5	262.5	257.6	252.6	247.6	242.6	237.8	233.0	228.2	223.6	219.0
$L_{MP,omf}$	2.8	3.1	3.1	3.1	3.1	3.0	2.9	2.9	2.8	2.7	2.7	2.6	2.5	2.5	2.4	2.3	2.3	2.2	2.1
$L_{Use-I,env}$	7.2	8.1	8.4	8.7	8.9	9.0	9.2	9.3	9.4	9.5	9.6	9.7	9.8	9.9	10.0	10.1	10.2	10.3	10.4
$L_{Use-II,lf}$	57.7	57.7	59.6	61.6	62.9	63.8	64.5	65.1	65.6	66.1	66.6	67.0	67.4	67.8	68.2	68.6	69.0	69.4	69.8
$L_{Use-II,OMF}$	58.4	58.4	60.3	62.3	63.7	64.6	65.3	65.9	66.4	66.9	67.4	67.8	68.2	68.7	69.1	69.5	69.9	70.3	70.7
In_{MP}	943.6	1052.1	1070.6	1090.6	1100.0	1102.6	1102.0	1100.0	1097.2	1093.9	1090.3	1086.6	1082.7	1079.0	1075.3	1071.9	1068.7	1065.8	1063.2
$Stock_{Use}$	873.0	903.6	935.2	967.9	1001.8	1036.9	1073.2	1110.7	1149.6	1189.8	1231.5	1274.6	1319.2	1365.4	1413.2	1462.6	1513.8	1566.8	1621.6
$\sum L_{Env}$	10.0	21.2	32.7	44.5	56.4	68.5	80.5	92.7	104.9	117.1	129.3	141.6	153.9	166.2	178.6	191.0	203.4	215.9	228.4
$\sum L_{OMF}$	531.2	1104.5	1690.2	2289.1	2895.3	3504.7	4115.6	4727.1	5338.7	5950.1	6560.9	7171.1	7780.6	8389.3	8997.3	9604.5	10211.2	10817.3	11423.1
$\sum L_{LF}$	402.4	839.4	1281.2	1728.4	2176.5	2622.6	3065.3	3504.1	3938.7	4368.8	4794.4	5215.4	5631.7	6043.5	6450.7	6853.5	7251.9	7646.1	8036.1